Principles

Renewable Energy

Analysis, Resources, Applications, Management, and Policy

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Edited by
Yarub Al-Douri

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PREFACE

The analysis, characterization, and application of renewable energies are some of the rapidly progressing areas of science and technology. Renewable energies are some of the most ubiquitous requirements on the globe; they have a variety of fundamentals, principles, and applications. Additionally, renewable energies are known to possess unique applications that were less known previously. Renewable energies give an assorted and appealing class of studies where their concepts exhibit a full spectrum of research, properties, and engineering types from solar to wind, thermal, hydro, and biomass. Furthermore, all assorted phenomena such as the increasing of manpower, educating society, building intellectual generation, and others could be noticed. Therefore, renewable energies have eminent importance of multifunctional application with a rich collection of studies and research that have a great potential for numerous applications.

The noticed high-quality renewable energies and related ones are important for the transition to a green economy and clean energy that prioritizes local resources, creates jobs, improves resiliency, and promotes energy independence. These data are necessary for creating great decisions—ranging from analysis, resources, applications, management, and policy. These reflect appropriate aspiration and cost-effectiveness and enable investment in renewable energy including various considerations and plans. The mentioned data can vary in quality and type and be cheaper or expensive; they describe the requirements for creating renewable energy decisions to analyze the data for the best recommendations to execute. Although these topics are correlated, they are generally organized to let renewable energy decisions be made or supported. They need to answer the following: What are the data required to support the target? What are the benefits and limitations of those data? What are the analyses required for the target?

Over the last three decades, the concept of renewable energy has emerged as a defining imperative of humanity that is situated at the nexus of science, technology, culture, economics, policy, and the environment. It is framed as a means to mitigate the negative impacts of fossil fuels, energy consumption, water consumption, and climate change. Due to the energy crisis, environmental, economic, political, market, and social issues, researchers have been attracted to develop sources of renewable energies to secure energy consumption, protect the environment, and promote regional development. The implementation of successful renewable energy that is sustainable in time has been related to participatory processes where views, expectations, and framings from different stakeholders become integrated.

Specific studies and reviews are implemented to cover a wide range of renewable energies. For applications, renewable energies can be successfully utilized for the best of humanity. Among the advantages of renewable energies, the most important is that they are cost-effective and robust in

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practical applications. Moreover, they can be fabricated and manufactured in various types of energy sources such as solar, wind, and others. For solar cells using nanotechnology, it can be used with techniques that are compatible with the traditional ones, which it is very important for large-scale production because the nanotechnology approach promotes cost-effectiveness, offers the possibility of manufacturing solar cells on a chip, and guarantees good reproducibility. Different types of renewable energies can be employed to be one of the most active research areas within the nanoscience community.

The ability to research different renewable energies and synthesize various applications significantly expands the range of properties that renewable energies can have—truly versatile and multifunctional for widespread use. A small change in their physical or chemical properties can be accompanied by variations of properties and behaviors. So, advances in analyzing and characterizing the techniques of renewable energies reveal numerous new functions.

Taking into account the importance of renewable energies, many books that are devoted to this class of energies have been released. However, during the past decade, great progress has been made on the analysis, characterization, and application of renewable energies and other properties as well as renewable energies' applications in a large number of studies that have been disseminated. So, it is decided to generalize the results of research in this direction and to publish this book devoted to renewable energies in developed and developing countries.

One should notice that the proposed book *Renewable Energy: Analysis, Resources, Applications, Management, and Policy* is the first and only one devoted to renewable energies. It is believed that this book could help readers and specialists in searching required information on the mentioned subject. It is planned that this book has a clear specialization by its content, which will provide interdisciplinary discussion for various renewable energies with a wide range of topics, from analysis and application to management and policy. This book is edited by a team of highly qualified experts, which guarantees that it has a high quality.

I hope this book will be comfortable and beneficial. I would hope that readers and specialists will consider it a reference of renewable energies that enables understanding the present status of renewable energies, estimating the role of multifunctional renewable energies in the fundamentals and applications for further research studies. The intended audience of the present book are scientists, academics, researchers, post-graduates, and engineers in the field of renewable energies.

I am sure that *Renewable Energy: Analysis, Resources, Applications, Management, and Policy* will be interesting for practicing engineers or project managers in industries and laboratories who would like to design renewable energies-based devices. With many references to the vast resource of recently published literature on the subject, this book will serve as a significant and insightful source of valuable information, providing scientists and engineers with new insights for understanding and improving existing renewable energies-based devices and for multiapplication. I believe it would be very helpful for university students, researchers, and academics. The structure assures to find useful information.

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The first chapter is devoted to the current world countenances in fulfilling the rapid increase in energy demand, decreasing greenhouse emissions, and improving energy efficiency at the same time. Furthermore, it additionally assumes a significant part in guaranteeing energy security, improving ecological safety, and expanding work in different nations. As of now, worldwide energy production is in a phase of new changes and developments. It discusses the new renewable energy trends and developments such as wind, solar, biomass, geothermal, tidal, and hydroenergy. The governmental guidelines and policies on renewable power generation and transmission and trending renewable energy storage technologies have been discussed. Followed by displaying renewable energy sources, solar and wind feature the steadily decreasing costs of electricity. However, the intermittency of their output makes them not suitable as stand-alone technologies for off-grid installations, and a large share of these intermittent renewables cannot be supported by electric grids. These "aggregated systems" are gaining considerable interest and, depending on the application, are called with different names: "virtual power plants," "microgrids," "multi-energy systems," and "energy districts." Moreover, improved performance can be achieved by adopting "hybrid systems" employing different renewable sources and/or technologies in the same energy conversion process. The mentioned chapter provides an overview of the most interesting options to integrate renewable energy sources as elaborated in Chap. 2. Chapter 3 has vastly explored the environmental Kuznets curve (EKC) hypothesis over the last 30 years. This research tries to expand the EKC hypothesis's validation for selected developed countries, specifically for G-7 (Canada, France, Germany, Italy, Japan, UK, and the USA). Additional explanatory variables as considered, such as renewable energy consumption, energy innovation, and foreign direct investment (FDI). Through the fully modified ordinary least square (FMOLS) econometric technique, a U-inverted linkage between economic growth and environmental degradation for the selected panel is observed, validating the traditional EKC hypothesis. Moreover, the evidence of the positive impact of renewable energy innovation on the environmental correction process is offered. Under the EKC scheme, this study's main finding is a non-linear connection between the FDI and carbon emissions. The results show a significant evidence of the role of FDI and renewable energy innovation as driving forces of the environmental correction process, while Chap. 4 has reviewed the most advances of nanotechnology to renewable energy production and storage. This aims to introduce several significant applications of nanotechnology in the renewable energy field. Nanotechnologies are attracting increasing investments from both governmental and non-governmental sectors that offer great opportunities to explore the new emerging nanodevices, such as quantum dots. This is to exploit specific properties that arise from the structure at a scale characterized by the interplay of classical physics and quantum mechanics. It is difficult to predict these properties *a priori* according to traditional technologies. Nanotechnologies will be one of the next promising trends. However, this study gives a deep survey regarding different aspects of the new nanotechnologies, such as materials, physics, and semiconductors, respectively, followed by several state-of-the-art nanodevices and then new nanotechnology features. This is followed by an introduction to the type of solar cells and the fundamental photoelectric process in them. Basically, the light absorption occurs in a semiconducting crystal, cluster, or molecule, subsequently inducing the formation of loosely bound electrons that are

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separated by an electric field created as a gradient in Fermi energies across the materials forming an interface. This simple principle has been embodied in all three generations of solar cells. Owing to their highly prolific research nature, third-generation solar cells are given higher emphasis in this chapter. The solar-to-energy conversion process and the rate limiting factors in sensitized and perovskite solar cells are provided, where the advancement of a nanostructured photoelectrode in overcoming the limiting factors is briefly discussed. Finally, the emergence of tandem photovoltaic is discussed, and a few difficulties in solar module production for third-generation solar cells are provided in Chap. 5.

Chapter 6 explains wind energy to be one of the cheapest and cleanest resources of renewable energy. It is very useful to use this wind resource to generate electricity because wind power is clean and efficient. Wind energy is the conversion of the wind kinetic energy into a useful form of energy, such as mechanical or electrical energy, that can be harnessed for practical use by using wind turbines. It reduces acid rain, smog, and pollutants to the atmosphere. Renewable energy has become popular in recent years due to the need for the utilization of more environmentally friendly energy sources. There are many concepts to classify the types of wind turbines. There are two basic designs of wind turbine classes based on the orientation of the rotor: the vertical axis wind turbines (VAWTs) and the horizontal axis wind turbines (HAWTs). The efficiency with which a rotor can extract power from the wind depends on dynamic matching between the rotor and the wind stream. Energy efficiency is a core pillar of sustainable development, which is realized through the adoption of integrated technologies that reduce energy consumption and increase the production of renewable energy and zero carbon dioxide emissions. African countries continue to progressively shift toward clean energy sources, which ensure the absence of health hazards to humans and the ecosystem. Efficient biomass energy, derived from living organisms, has the potential to contribute to increased energy efficiency with adequate adoption of good practice and better institutional capacity. Thus, Chap. 7 examines the role an institutional framework plays in ensuring the increased access and the utilization of biomass energy in Africa. The overview of ocean tidal and wave energy is provided in Chap. 8. Various ocean energy sources such as tidal and wave energy are good sources of energy for the increasing demand for energy and reducing non-renewable resources. There are many shortcomings and needs for development in this sector for energy production that needs to be addressed. We have discussed the existence of tidal wave energy resources around the world, wave energy potential and technology in use, and wave power potentials in different countries. On the otherside, Chap. 9 presents the ever increasing population's demand in using various forms of energy in the form of heat, light, and similar others. Non-renewable energy resources, such as coal, petroleum, and natural gas, are efficient energy producers, but create much environmental pollution through increasing the carbon footprint. The sources are fast exhausting too due to somewhat fickle policies adopted time and again and irresponsible and unplanned uses. It is, therefore, necessary to move into the form of energy that is environment friendly and also not limited. Geothermal and hydroelectric energies are of this kind and, thus, have been explored of late with much commercial interest. On the other hand, hydropower uses rainwater as a source of energy. The telecommunication and Information and Communication Technology (ICT) industries have grown

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tremendously fast with increasing demand for modern value-added services and pervasive computing as given in Chap. 10. This rapid and radical deployment of cellular base stations and the networking infrastructure throughout the world has significantly increased energy consumption, resulting in emitting harmful greenhouse gases and increasing the annual electricity bill for mobiles, which has a direct impact on the consumers. Introducing renewable energy to power cellular network base stations and an ICT infrastructure makes not only environmental, but also—most importantly—of economic sense, while at the same time opening opportunities for new business models. Thus, it is of great importance to study the subject in order to determine the potential gains, applicability scenarios, deployment strategies, and policies, which is the focus of this chapter.

Chapter 11 has archived sustainability and energy production; the utilization of renewable energy sources is increasing dramatically. To fulfill this requirement, the optimal management of energy resources is evitable against climate changes. The rural areas' management still needs to use the strategy and concept of urban planning and design, which is laborious and time-consuming. It scientifically interprets the scientific connotation of rural revitalization strategy and conducts a summative research on beautiful rural planning. Interactive energy sharing networks with centralized coordinated energy management between vehicles and buildings can increase eco-economics viability, while tracking battery degradations is critical to the energy flexibility and techno-economic performance assessment. This is formulated as a synergistic interactive energy framework for flexible district energy management, involving the renewable systems of solar-wind, mobile and static battery storage, and demands of diversified energy in district buildings. The optimized size with the management of energy strategy is a transition toward 100% sustainability to investigate a renewable energy-based microgrid. Therefore, an optimized capacity size involving the management of energy strategy is proposed to overcome challenges facing microgrid operations and planning. Also, to research the economies decarbonization, it is required to address the climate change. This is for understanding firms' and consumers' incentives in the presence of asymmetric information to determine strategic interaction, the impact of market design, and the market structure on the competition intensity. This is followed by Chap. 12, which present a state-owned utility company that is efficient and green should be the common goal that every country should achieve. However, the power and market concentration of *Perusahaan Listrik Negara* (*PLN*) is often seen as a major hindrance to renewable energy (RE) investment. Independent power producers (IPPs) have to deal with the uncertainty in regulation and tariff negotiation with PLN as the single off-taker of all electricity projects in the country. Practices ranging from unstandardized power purchase agreements (PPA) and the unlevel playing field with coal have deterred RE projects. Beyond those challenges, Indonesia needs to address its electricity governance as a more fundamental issue to achieve the ambition of renewable energy target (RET) by 2025 and, more recently, the proposal of the net zero emissions (NZE) target in the power sector by 2050. The result contributes to the ongoing discourse regarding the current challenges of decarbonizing the electricity sector through RE concurrent with the implementation of market-based reforms in an emerging economy. The deployment of renewable energy sources has been discussed intensively in Chap. 13 from both economic and technical points

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of view. However, the large-scale deployment of renewable energy sources must go beyond single projects and involve a large variety of stakeholders as well as broad public support. Therefore, the human factors in energy transition connected to the deployment of renewable energy sources become important. These human factors include social and public support for renewable energy projects as well as willingness to use technology, pay for electricity generated by renewable energy sources, and participate in decision-making processes around the implementation of renewable energy projects. This contribution reviews experiences with the deployment of renewable energy sources in various countries, with a particular focus on Austria and Jordan. The results show that this process is a wicked policy problem that involves a variety of interests and opinions. The renewable energy potential and its status in specific developing countries such as Iraq, Saudi Arabia (KSA), Algeria, Morocco, Pakistan, and Malaysia are presented in Chap. 14. An outlook into the profile of Iraq at existing electricity generation with crude oil production at the present level with accompanying gas flares cause CO_2 emission as well as the industrial, human activities and the grid electricity distribution have been accounted for. The KSA national oil consumption is increasing by 7% annually. If this growth rate continues, the local demand will be doubled in a decade. The Algerian economy is strongly dependent on the fossil fuels' market where 93.6% of its exportations are mainly oil and natural gas. The Moroccan authorities are fully aware of this challenge, especially with the population and economic growth that causes a sharp increase in energy demand. The wind, hydro, solar, biomass, and geothermal energies potentials have been presented. Moreover, it is found that technological innovation and renewable energy are negatively associated with environmental degradation, showing that globalization is also an important source of increase in CO_2 emissions in Pakistan. Finally, in Malaysia, the performance of research and development (R&D) activities in the renewable energy resources of solar, wind, biomass, biogas, and mini-hydro is explored. Chapter 15 has introduced residential communities in remote areas that are distinguished by their spacing and dispersal so that connecting them to the electricity grid is costly. This chapter studies the potential of renewable energies in delivering electricity to such remote residential communities and replacing the national grid.

Finally, I thank all the contributing authors. I am thankful that they have agreed to participate in the preparation of this book. Without their efforts, this book would have not been possible. I also express my gratitude to AIP Publishing for giving us the opportunity to publish this series. I especially thank the AIP Publishing team for their patience during the whole process of production and for encouraging us during the various stages of preparation.

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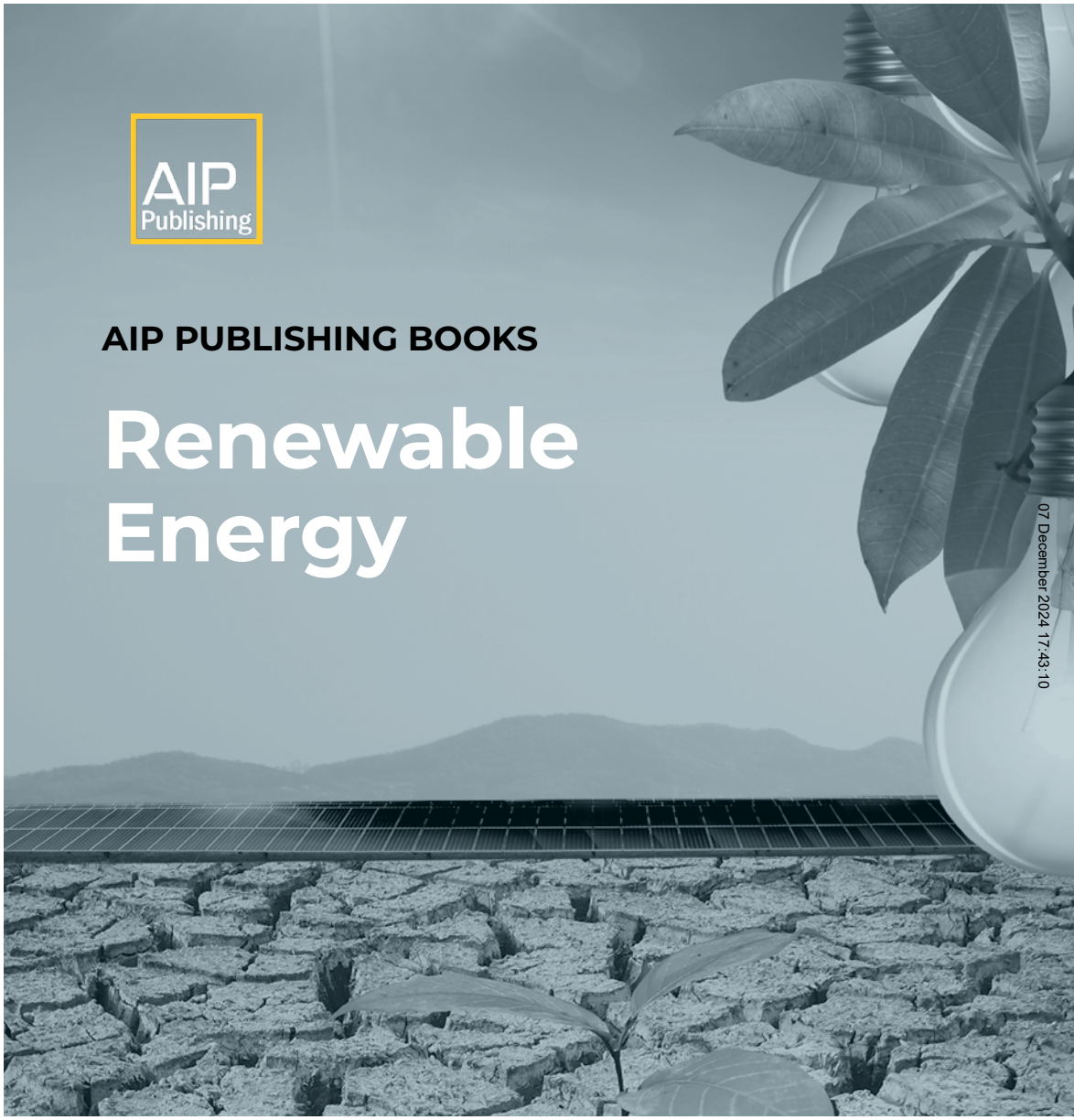
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CHAPTER

1 RENEWABLE ENERGY ANALYSIS AND RESOURCES

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1.1 INTRODUCTION AND BACKGROUND

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According to the definition of the International Energy Agency (IEA), "renewable energy is the energy that is derived from natural processes that are constantly replenished such as solar, wind, biomass, geothermal, hydropower, ocean resources, electricity and hydrogen derived from those renewable resources" (OECD, 2014). One of the most critical issues in building sustainable energy solutions is to handle the energy trilemma, which is based on three dimensions: the security of energy supplies, affordable energy sources, and reducing carbon emissions to sustain the environment (Bale *et al.*, 2015). The increased consumption of different types of energy, including fossil fuel sources to supply the essential services for humans like lighting and heating, has caused not just genuine climatic changes but also an energy-security problem in case of sudden energy cuts, which may influence human existence negatively and risk the eventual fate of next generations. Fundamentally, the solid admittance to different kinds of energy consistently and in satisfactory sums and normal costs that do not negatively sway the climate and the economy is regularly considered the energy security definition (Zhu *et al.*, 2020a). On 11 December 1997, delegates from around the world gathered in Kyoto, Japan, to sign the Kyoto Protocol. This agreement set in motion the policy of the United Nations to combat climate change by limiting CO_2 emissions. While the agreement was approved in 1997, it did not take effect until 2005. The added focus on climate change has contributed to an international focus on reducing CO_2 emissions from electricity production. In 2019, IRENA published the Global Energy Transformation: A Roadmap to 2050. According to the 2019 edition, the share of the renewable energy in the world's total energy consumption must be scaled up a minimum of six times faster for the planet to satisfy the decarbonization and climate mitigation objectives set out in the Paris Agreement (International Renewable Energy Agency, 2019). Figure 1.1 represents the key milestones over the past 20 years in renewables from 1997 to 2019. A worldwide energy transition is urgently required

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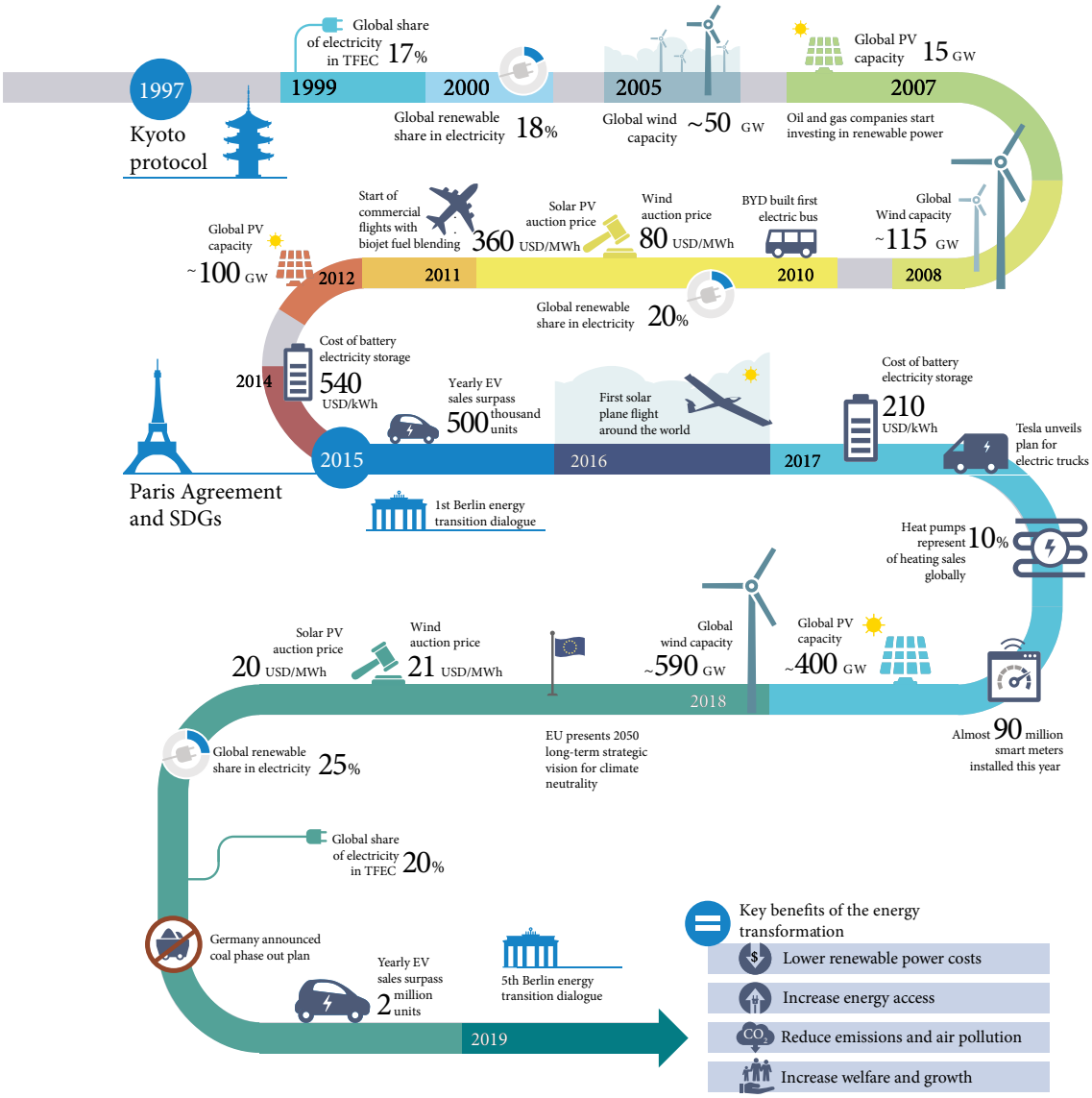
1997
Kyoto protocol
1999
Global share of electricity in TFEC 17%
2000
Global renewable share in electricity 18%
2005
Global wind capacity ~50 GW
2007
Global PV capacity 15 GW
Oil and gas companies start investing in renewable power
2008
Global Wind capacity ~115 GW
2010
BYD built first electric bus
2011
Wind auction price 80 USD/MWh
Solar PV auction price 360 USD/MWh
Start of commercial flights with biojet fuel blending
2012
Global PV capacity ~100 GW
Global renewable share in electricity 20%
2014
Cost of battery electricity storage 540 USD/kWh
2015
Paris Agreement and SDGs
Yearly EV sales surpass 500 thousand units
1st Berlin energy transition dialogue
2016
First solar plane flight around the world
2017
Cost of battery electricity storage 210 USD/kWh
Tesla unveils plan for electric trucks
Heat pumps represent 10% of heating sales globally
2018
Solar PV auction price 20 USD/MWh
Wind auction price 21 USD/MWh
Global wind capacity ~590 GW
Global PV capacity ~400 GW
Almost 90 million smart meters installed this year
EU presents 2050 long-term strategic vision for climate neutrality
Global renewable share in electricity 25%
Global share of electricity in TFEC 20%
Germany announced coal phase out plan
Yearly EV sales surpass 2 million units
5th Berlin energy transition dialogue
2019
Key benefits of the energy transformation
Lower renewable power costs
Increase energy access
Reduce emissions and air pollution
Increase welfare and growth

FIG. 1.1
Key milestones over the past 20 years in renewable energy development (International Renewable Energy Agency, 2019).

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to restrict worldwide surface temperature increase under 2 °C. Thus, successful transformation is determined to be possible; it will require the fast advent of policies to apply coordinated initiatives for integrating worldwide issues, like climate change, into national and local policy concerns. One hundred and ninety-three nations authorized the sustainable development goals (SDGs) in September 2015. This is formally called the 2030 Agenda for Global Development of SDGs, including developing and developed nations. Energy and power are crucial demands of every country, and their importance has emerged in the energy industry, including transportation (Ahmad and Zhang, 2020). Nations outside of the Organisation for Economic Co-operation and Development (OECD) are anticipated to represent 64.0% of 739 quadrillion Btu of the overall world by 2040.

The shift in the share of production of the whole gross domestic output results in more considerable energy requirements and usage variations. Asia is forecasted to be the biggest shift in energy usage in non-OECD nations. In contrast, China's development results in a boost in the percentage of energy-intensive products produced worldwide. India's per capita earnings and energy requirements continue to lag in the different bigger economies (Capuano, 2018). Gas levels of the greenhouse that contains many of them, including carbon dioxide, have risen considerably worldwide, which empowered governments and ventures to consider an alternative to environmentally harmful fossil fuels (Alkan and Albayrak, 2020). CO_2, CH_4, and N_2O are the three well-mixed atmospheric greenhouse gases (GHGs) that contribute most to the current global warming, as shown in Fig. 1.2. Since the beginning of the industrial period (1861–1880), their concentrations have risen, causing much of the current temperature to rise above the average global temperature. The 2 °C allowed temperature rise limit above the Paris Agreement's average for 2100 requires a significant reduction in GHG emissions over the next few decades (World Meteorological Organization and Global Atmosphere Watch, 2019). The most significant anthropogenic GHG emission in the atmosphere is carbon dioxide (CO_2), contributing to about 66% of the radiative forcing of long-lived greenhouse gases (LLGHGs). Over the past decade, it was responsible for about 82% of the rise in radiative forcing and about 81% increase over the past five years. On the other hand, approximately 17% of LLGHGs radiative forcing leads to methane (CH_4). Natural sources release about 40% of methane into the atmosphere like termites and wetlands, whereas 60% originates from anthropogenic sources like fossil fuel exploitation, rice agriculture, cattle farming, biomass burning, and landfills (Marielle Saunois *et al.*, 2019). The third most significant GHG emission is nitrous oxide (N_2O). Around 6% of radiative forcing by LLGHGs comes from it. N_2O is released from natural (about 60%) and anthropogenic (about 40%) sources into the atmosphere, including soils, oceans, biomass burning, the use of fertilizers, and different industrial processes.

One hundred and twenty-six nations around the globe have renewable energy policies that incorporate a wide assortment of innovations and sources. These policies range from direct investments, codes, tariffs, grants, strategic, plans, regulatory instruments, and financial incentives and are executed dominatingly at the public and state levels. While arrangements between nations differ regarding the advances they incorporate, fusing the broadest scope of advancements in our investigation gives the most preparatory gauge of conceivable ecological equity suggestions. In our concise audit of the IEA

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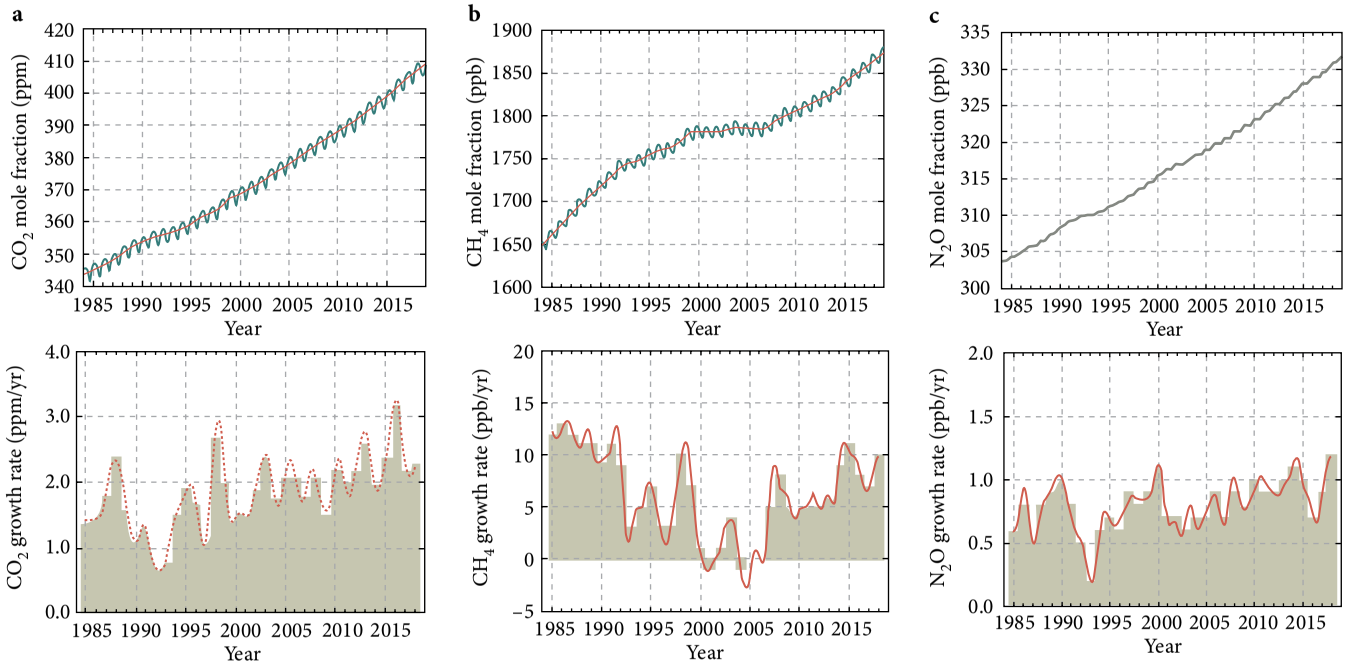

FIG. 1.2
Globally averaged mole fraction (ppm) and its growth rate (ppm/year) from 1984 to 2018: (a) CO_2, (b) CH_4, and (c) N_2O (World Meteorological Organization and Global Atmosphere Watch, 2019).

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approaching their information base (842 arrangements), all in all, U.S. state-level RPSs are the generally comprehensive of the broadest scope of renewable energy innovations and technologies (Levenda *et al.*, 2021).

1.2 RENEWABLE ENERGY SOURCES

There are many renewable energy sources (RESs) such as sunlight, wind, geothermal, biogas, biomass, waves, tides, and ocean currents. Renewable energy technologies receive heat, power, or mechanical energy and transform them to motive power or electricity. Efficient activities should be started quickly to reduce the negative ecological impacts of climate change and global warming problems, just as productive and economical RESs should be investigated. The cost of electricity from RESs has gradually decreased over the last few years, as per the IRENA report (International Renewable Energy Agency, 2018). As per the statistics delivered by BP (BP, 2020) in Fig. 1.3, since 2009, the total worldwide energy consumption has kept expanding with a cumulative increment of 15.10% in 10 years. The consumption growth rate in 2017 has been growing for two successive years, arriving at the most significant development rate since 2013, which was higher than the regular annual growth rate over the previous decade. The consumption of renewable energy has kept on developing emphatically. In 2017, the worldwide renewable energy consumption grew at a yearly pace of 5.62%, which was 2.95 times

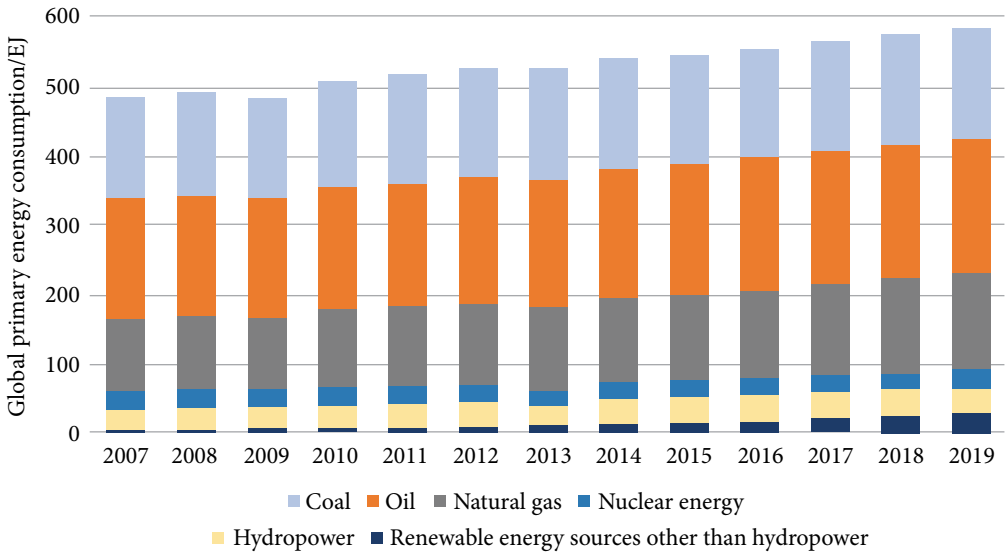

FIG. 1.3
Changes in global primary energy consumption (BP, 2020).

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higher than the annual development pace of essential energy consumption. Among them, hydropower development was moderately lethargic, with a development pace of just 0.56%. Other renewable energy source's development pace was as high as 16.64%, which was around multiple times higher than the yearly development pace of fossil energy consumption, demonstrating a solid development pattern. In 2017, the absolute worldwide renewable energy consumption was 58.84 EJ. The expansion was somewhat lower than in 2016 yet over the ten-year normal, and the complete growth in the ten-year term was about 62.98%.

The portion of renewable energy consumption has expanded consistently, increasing 41.59% from ten years ago (Li *et al.*, 2020a). Renewable energy sources have acquired expanding consideration of governments around the globe due to the favorable circumstances they have over fossil fuels. Consequently, renewable energy strategies with clear objectives worldwide are being created and executed to encourage the development of the renewable energy field. The European Union (EU) directive on renewable energy requires that not less than 20% of the overall generated energy of the EU should be generated from renewable energy sources by 2020 (Aboagye *et al.*, 2021). There are different motivations to redirect toward RESs, including a decline in the expenses of energy production from RESs, a decrease in carbon emissions, the reliability of the renewable energy technologies, and the unique nature of this industry. The cost of electricity from photovoltaic (PV) cells dropped by right around 3/4 in the time frame between 2010 and 2017 while wind turbine costs have diminished by about half in an equivalent time span, which prompts less expensive wind energy (Hannan *et al.*, 2020). As shown in Fig. 1.4, the global composition of renewable power capacity was shifted during

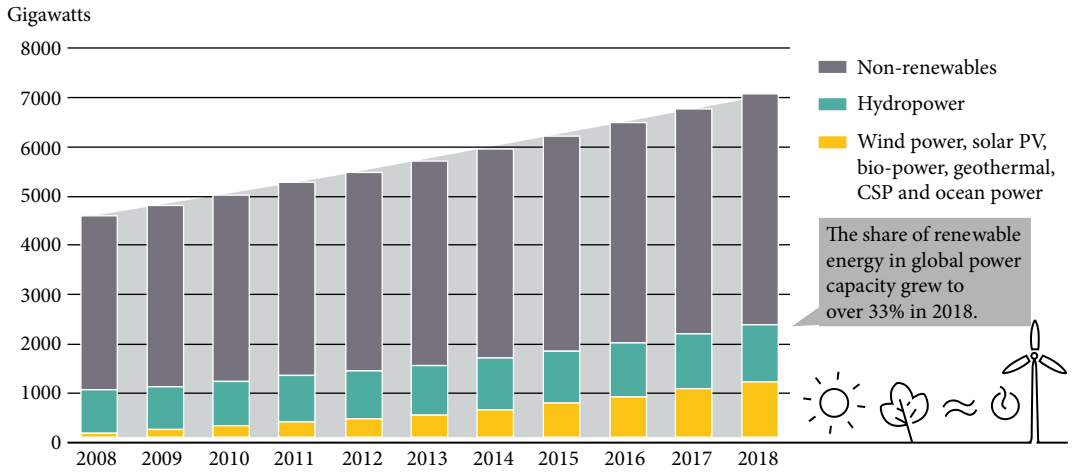

FIG. 1.4
Global power generating capacity, by source, 2008–2018 (REN21, 2019).

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2018. Hydropower was no longer accounted for half of the total renewable power capacity, hence falling below 48% by the end of 2018. On the other hand, wind power comprises 25% of the installed renewable power generation capacity, and solar PV exceeded 20% for the first time. Overall, renewable energy has grown to account for more than 33% of the world's total power generating capacity (REN21, 2019).

1.2.1 Solar photovoltaic energy

Photovoltaic (PV) technology can be categorized into three generations. First-generation technology is based on silicon such as monocrystalline, polycrystalline, and ribbon sheets. Second-generation technology is based on thin films such as amorphous silicon, cadmium-telluride (CdTe), copper indium gallium diselenide (CIGS), and multi-junction cells.

Third-generation technology is an emerging one that uses perovskite, passivated emitter and rear cells (PERCs), and nanocrystalline films. According to a study done in 2014 by Ramanujam *et al.* (2016), the market share of polycrystalline was 56%, and 36% for the monocrystalline-based solar cell was predominant. The rest distributed as 5% for CdTe and 2% for CIGS, and less than 1% for amorphous silicon. Different types of nanomaterials have been used in developing photovoltaic solar cells such as TiO_2 (Elsaeedy *et al.*, 2021), ZnO (Abood *et al.*, 2021), SnO_2 (Qureshi *et al.*, 2021), Rh_2MnZ (Mentefa *et al.*, 2021), CdS (Al-Douri *et al.*, 2019), $CuInS_2$ (Alalousi *et al.*, 2021), and metal oxides (Abu Odeh and Al-Douri, 2020) to enhance their efficiency and reduce the production costs of the generated electricity. Perovskite-based solar cells have been used, and different emissions might be released into the environment either directly or indirectly as a result (Kwak *et al.*, 2020). There are four major components of any solar system: the cells, batteries, inverter, and the attached load. These solar components should be selected according to the cost, size, and application. The solar system design should consider the capacity of the required generated energy, economic feasibility, and reliability. Since PV system batteries are charged and discharged very often, higher capacity batteries are recommended. There are different types of batteries, such as valve-controlled and flooded batteries. Flooded batteries require more maintenance, so they can last longer, whereas valve-controlled batteries need less maintenance. Another critical part of the solar system is the inverter. There are many types available, but not all of them are suited to PV systems. When the power conversion efficiency of the PV inverter is low, the power produced by the PV array cannot be effectively supplied to the utility. To increase the efficiency of power, it is very important to use well-designed circuit technology to eliminate the switching and conductive losses of semiconductor devices as well as the power losses incurred by the interconnection of cables. In fact, several studies suggest improving the reliability of PV systems by optimizing the output capacity of the systems (Al-Shahri *et al.*, 2021). Stropnik and Stritih (2016) increased the photovoltaic panel's power output and electrical efficiency using the phase change material (PCM) of RT28HC. Adding PCM material enhanced the performance by 14%. A few research studies have focused on using geospatial technology to analyze solar energy potentials and determine suitable locations for installations (Chiemelu *et al.*, 2021). Solar irradiance is a critical piece

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of data for such geographical solar energy investigations. Obtaining this for a big region via typical field observation methods is frequently time-consuming and costly. However, ways for obtaining them from certain satellite photos have been created. Previous research (such as Hammer *et al.*, 2003) utilized satellite photos to calculate surface solar irradiance using the HELIOSAT approach. Huang *et al.* (2019) conducted a review of the different methodologies and advances achieved in calculating surface solar irradiance using remote sensing (RS) satellite photos. There are many geospatial techniques to find the optimal and best place for creating a solar power park to identify suitable locations. Slope analysis, land use, land cover categorization, and site climatic variables to conduct site suitability analysis can be used. Chaves and Bahill (2010) created an algorithm that uses six basic inputs to locate ideal places for solar panel installations: the digital elevation model (DEM), aspect, slope, radiation, bare earth properties, and some mask. Geospatial technologies such as Geographic Information System (GIS) and remote sensing (RS) have shown to be useful in the assessment of renewable energy resources across the world. GIS applications have been utilized to give critical information for decision-making in a variety of study fields, including natural resource management, environmental pollution and hazard reduction, regional planning, urban development, and utilities management (Zhu *et al.*, 2020b). The application of geospatial approaches for environmental modification, such as site selection, often entails the integration of many environmental variables or factors to incorporate numerous variables utilized in multi-criteria analysis; geoprocessing tools such as ArcGIS Model Builder are typically employed (Ebistu and Minale, 2013). Ganiyu *et al.* concluded that a typical PV system consists of the following basic components: (i) PV solar array collectors, (ii) power conditioners, (iii) energy storage system, and (iv) solar inverters. PV arrays convert solar energy from sunlight to direct current electricity, and the conversion rate is determined by insolation. A blocking diode placed immediately after the arrays ensures that the array generated power goes exclusively to the power conditioner and reduces the backward flow of electricity that may occur during low insolation when the battery discharges back to the solar array. The power conditioner is made up of a maximum power point tracker (MPPT), a battery charger, and a discharger controller. The MPPT ensures that the maximum power generated by the PV array is extracted at all times, whereas the charge–discharge controller acts as a charge regulator, preventing over-charging and over-discharging of the energy storage bank (batteries) required to store the electricity generated by the PV array conditioner (Ganiyu *et al.*, 2020).

1.2.2 Wind energy

Until recently, the United States was the world's greatest user of energy, but China has just overtaken U.S. consumption levels. Because of the volume and worldwide effect of U.S. energy use and parallels in political influence on energy policy, the findings of this research are of worldwide relevance. Despite the fact that the U.S. government began supporting wind energy in 1978, the great bulk of wind energy growth has happened in the twenty-first century (Brown *et al.*, 2012). Only four years from 2000 to 2004 had annual capacity increases of less than 10%, while from 2005 to 2009, U.S. wind power capacity rose at a 39% annual pace (Lu *et al.*, 2011). In recent decades, wind power has been widespread across the world for the production of electricity. By the end of 2020, global cumulative wind power

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installations are expected to hit 741.7 GW. According to the World Energy Outlook 2019, the increase of generation from wind and solar PV assists renewables in overtaking coal in power generating mix in the mid-2020s. As shown in Fig. 1.5, low-carbon sources will account for more than half of total power generation by 2040, with wind and solar PV leading the way (IEA, 2020). Technically, the estimation of wind energy resources is necessary for calculating the annual output of electrical energy from wind energy at different locations.

Accurate records of typical wind speeds and their predictive characteristics are critical for estimating the capacity of wind energy. In general, wind energy worldwide can be classified into two types: onshore wind and offshore wind. As a result, wind power production is made up of inland and offshore wind turbines. To date, much of the wind power has been provided by onshore wind turbines (Li *et al.*, 2020b). As the wind is becoming an increasingly significant and efficient source of energy production in many power markets, policymakers need to negotiate wind energy prices based on transparent and accurate statistics. The price dilemma is compounded by the variety of wind technologies, asset management strategies, and

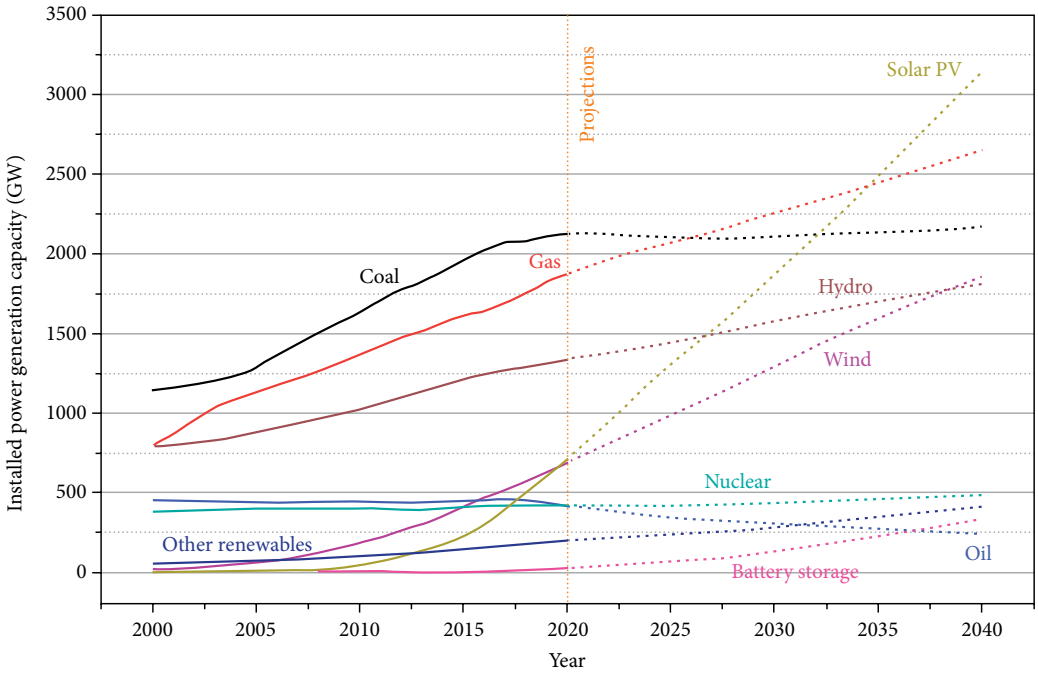

FIG. 1.5
Installed power generation capacity (GW) in the stated policies scenario 2000–2040 as stated in World Energy Outlook 2019 (IEA, 2020).

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differences in international project cost estimates. Increasing wind power impacts wholesale electricity prices in many countries and contributes to shifts in the value of wind energy itself (Duffy *et al.*, 2020). Connections between wind farms and the current electricity system are frequently disregarded. Because many wind farms are located distant from the population areas that consume the electricity, energy grid connectivity is a key challenge. To be linked to the current power grid, wind energy growth necessitates a considerable investment in high-voltage transmission lines (Lesser, 2013). Additional study on wind energy transmission lines financial costs and environmental impacts would be beneficial to the renewable energy profession (Dorrell and Lee, 2020). Although the CO_2 reduction advantages of wind energy are obviously beneficial compared to traditional fossil fuels, it is equally crucial to examine the negative environmental externalities associated with wind farms (Kreuter *et al.*, 2016). Landscape degradation and habitat degradation, as well as noise pollution, have all been mentioned in previous research studies as detrimental environmental consequences (Zerrahn, 2017). Researchers have looked into adverse economic effects such as potential market distortions and energy excess storage challenges (Green and Vasilakos, 2010). Hydro-wind hybrid power generation has shown to be one of the viable, clean power generating options given water and wind energy properties. As an adjustable and energy source, hydropower can firm wind power, balance wind deviation by providing significant spare capacity and flexibility, decrease anticipated and real wind production discrepancies, and smooth wind power output. Furthermore, the distribution of hydro- and wind energy in time is governed by the law of low rainfall and windy weather in winter and spring and slight wind and heavy rain in summer and autumn. In this approach, wind and hydroenergy complement each other better in time. When the wind power generation fluctuates in the hydrowind hybrid power generating system, the hydropower station adjusts the generator to compensate. Wind energy is abundant not just in coastal or island places but also in rural and flat locations. The coastal, of course, is surrounded by water. If the rural is located near a river, it will be the best location for establishing a hydrowind hybrid power system (Peng *et al.*, 2021).

1.2.3 Hydroenergy

Solar energy is a renewable energy source that is global, limitless, clean, and ecologically beneficial. However, the most significant disadvantage of solar energy is its volatility and intermittency, and the quality of solar electricity is heavily dependent on the season and weather. Wind energy, like solar energy, is a type of renewable energy source. However, when wind penetration grows, the quality of power supply is substantially jeopardized due to its features. Wind energy is difficult to anticipate due to its unpredictable and intermittent character, and the accuracy decreases with time, which may result in economic losses (Impram *et al.*, 2020). Hydro-energy is a clean, easy-to-schedule renewable energy source, and using water for power generation is highly efficient, of low cost, and has a lower environmental effect. Hydropower is not only a significant role in the entire usage of water resources in many nations, but it is also one of the primary power generating sources. However, there are several limits in terms of available hydroenergy. For example, hydropower may be highly influenced by natural factors such as rain, and the cost of building hydropower facilities is considerable, making capacity expansion challenging. The ideal location, size, and plan of the hydroelectric power plant (HEPP)

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includes local topographies and geological conditions, the availability of water and head, the need for energy, the site's availability, and environmental issues as several variables that need to be considered. Adequate functional performance and safety are the most important elements of a HEPP construction. Hydropower is an energy created by turning the kinematic water energy into electrical energy. The renewable energy system is regarded to be the most frequently deployed kind. HEPP emits carbon dioxide and other greenhouse gases much lower than fossil fuels, and its total life cycle has a lesser environmental impact. Moreover, owing to the wide footprint of the biological effect of reservoirs and other required regions of the development, the environmental consequences of hydropower are likely to be larger than any type of energy generation (Şen, 2018). The discharge fluctuation, albeit a vast reservoir is provided to maintain a certain flow, is a basic disadvantage of hydropower. Temporary fluid flow variance can diverge in a lengthy yearly cycle by a factor of 5–10, which causes an intrinsic disruption of the grid's power supply. One way to mitigate this is to build consistent reservoirs, which may pump water into higher elevations with the use of surplus power when high water flows occur. This technology contributes to controlling the power generation but at the cost of significant power loss.

1.2.4 Tidal energy

The tide generates forces that mostly come from the interconnected Earth–Moon system. The tidal power plants are described as dams built where the tidal range is enough to generate energy cheaply at turbines. The major parts of the main space power station are the embankments that constitute the impoundment's main artificial outlines, with a minimum length while increasing the surface area surrounded by the plane. A significant element in the design of the slope is the reduction of the natural tides flow disruption. In addition, turbines are positioned across the bench in the waterways and transform the potential energy generated by the head difference into rotating energy and then to power through generators (Neill *et al.*, 2018). Tidal streams, like tidal elevation, are predictable; thus, combining the phasing of suitably large tidal stream arrays with tidal lagoons has the potential to improve the baseload production capacity from various facets of a single renewable resource. Because both the tidal range and the tidal streams display intermittency on spring/neap timeframes, they do not always provide peak generation at times of peak demand. Tidal energy phase optimization in conjunction with wind and wave energy, which naturally peak during the winter months, may help address this seasonal variability in demand; however, suitable predictive, coupled modeling techniques should be used to robustly assess the true generating potential and interactions between technologies and schemes (Widén *et al.*, 2015; and Angeloudis *et al.*, 2016). The problems faced by this sort of energy are environmental because flow change has biological and ecological effects: it will directly influence benthic habitats and on all species that spread through the free-floating of larvae. Changes in sediment transportation, mixing, and other physical processes may impact diving birds and pelagic predators/prey interactions. At the same time, the cost of electricity from marine power technology, the discounted project costs for life split by its energy output for life, is particularly sensitive to changes in the energy output and, therefore, the income that may be produced by interactions between the range of energy sources. This is because it combines high fixed costs with very low marginal generating costs

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(Waldman *et al.*, 2019). Successful deployments and operations of turbines within those environments require better analyses of the implications of increased energy-extraction scenarios on the environment and the ecosystem and, in particular, the effects on marine quality. In fact, as the energy of tidal streams contributes to significant water transportation in estuarine and coastal marine systems, system-wide changes in hydrodynamic circulation and the transportation of water particles may be caused by operating turbine arrays. This involves trapping and dispersing changes of the dissolved nutrients and contaminants (e.g., petroleum, persistent poisons), organic particulate matter (e.g., plankton, gametes, larvae), and sediments. Large-scale effects are also predicted on biological processes, such as dissolved oxygen renovation or primary generation (Guillou *et al.*, 2019).

1.2.5 Geothermal energy

Geothermal energy is heat derived from the earth's subsurface. It is found in the rocks and fluids underneath the earth's crust, all the way down to the earth's boiling molten rock, magma. To generate electricity from geothermal energy, wells are sunk a mile deep into underground reservoirs to obtain the steam and hot water, which is then utilized to drive turbines attached to electricity generators. Geothermal power facilities are classified into three types: dry steam, flash, and binary. The earliest kind of geothermal technology, dry steam, extracts steam from the earth and utilizes it to spin a turbine directly. Flash plants convert high-pressure hot water to cool, low-pressure water. In contrast, binary plants convert hot water to vapor by passing it through a secondary liquid having a lower boiling point. Less than 1% of total global energy demand is met by geothermal energy. It was noticed in 2015 that the global geothermal energy capacity climbed to 13.20 GW due to a significant addition of 315.0 MW. The geographic locations of geothermal energy farms, which supply about 72.01% of total global geothermal energy potential, are nearby Rim-Pacific hotspot features (Ahmad *et al.*, 2020). An unstable rate of total geothermal energy installation capacity of roughly 43.01% is located in island nations or areas and suitable for applications such as heating, energy generation, and heat storage under ambient circumstances. The greater upfront cost of resource classification and exploration is a key barrier in proposing alternative geothermal locations. Recognizing the productive potential of such geothermal sources necessitates the use of quick models and low-cost technologies for evaluating and finding unmeasured geothermal energy resources (Tareen *et al.*, 2018). The information provided on direct geothermal heat applications is based on nation updates submitted to the World Geothermal Congress 2020 (WGC2020). As stated at the end of 2019 for global geothermal direct use, the total installed capacity was 107.727 MW, an increase of 52.0% compared with the WGC 2015. The overall annual energy consumption is 1.020.887 TJ (283.580 GW h), an increase of 72.3% over the WGC 2015 and an annual growth compound of 11.5% (Lund and Toth, 2021).

1.2.6 Biomass energy

Biomass is any organic substance originating from plants or animals that are alive or have been dead for a brief length of time. In plants, biomass is created when carbon dioxide in the atmosphere is converted

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into carbohydrates in the presence of sunlight. Biological species will subsequently proliferate by devouring these botanical or other biological species, contributing to the biomass cycle. Bioenergy obtained from biomass is a renewable source of energy that may be used to generate energy in place of nonrenewable sources such as coal. However, compared to coal, biomass, as given by nature, has a lower energy density, greater moisture, and more volatiles. As a result, biomass requires a pretreatment procedure to enhance its qualities before it can be utilized in conjunction with or as a replacement for coal (Mamvura and Danha, 2020). To count toward European Union (EU) objectives and be eligible for funding, biofuels and bioliquids must meet all sustainability requirements. The Renewable Energy Directive 2009/28/EC (RED) prohibits the use of many land types for biofuel production, including high biodiversity value land (primary forests, nature conservation areas, extremely biodiverse grassland), high carbon stock land (wetlands, wooded regions), and peatlands. The cross-compliance rules include the protection of soil and water quality, biological variety, the use of fertilizers/pesticides with caution, and air pollution. The influence of biofuels and bioliquids on biodiversity, water resources, water quality, and soil quality, as well as the reduction of GHG emissions, changes in commodity pricing, and land use linked with increased biomass usage, must be investigated. Fuel providers are expected to report on their compliance with the sustainability standards, as well as the actions they have done to preserve soil, water, and air; restore degraded land; and minimize excessive water usage in water-stressed regions (Scarlat *et al.*, 2015). The expansion of direct renewables use in end-use sectors (buildings, industries, and transportation) would provide a 0.3%-point yearly renewables share increase, accounting for almost a fourth of the total. In 2050, biomass would account for two-thirds of direct renewable energy usage. Modern biomass heating applications and liquid biofuels are examples of this. Annual bioenergy supply would approximately quadruple from current levels to around 116 EJ in 2050 in terms of primary energy. This involves a transition away from old biomass uses and toward contemporary applications such as modern kitchen burners. Direct usage from the manufacture of liquid transportation fuels would account for around one-third, with the remainder coming from industrial uses, conversion into electricity, and district heating (Gielen *et al.*, 2019).

1.3 RENEWABLE ENERGY TRANSMISSION

Given the geographic variety required to build a reliable VRE-dependent power system, the location of VRE generators will not simply integrate with the infrastructure developed for earlier power production sources. Optimal VRE locations are frequently located distant from urban demand centers, necessitating the development of novel carbon-free ways of delivering this energy. Because of its capacity to carry huge amounts of energy over long distances with low losses, high-voltage direct current (HVDC) transmission lines are frequently regarded as perfect for energy transport (Semeraro, 2021). When the analytical method concentrates on particular current or prospective transmission projects, two major problems may result in overestimation of VRE transmission costs. First, because of the many goals and advantages of transmission, such as increased dependability and reduced congestion, defining the right financial responsibility for VRE transmission is challenging. The consequent underestimation of VRE

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transmission costs is exacerbated by VRE's comparatively low-capacity factors, resulting in reduced overall utilization of transmission projects completely assigned to VRE integration. Second, when you concentrate on VRE projects that need to be upgraded rather than on all VRE projects, some of them may not need to be retransmitted (Gorman *et al.*, 2019). The considerable growth of environmental concerns has led to an increased usage of renewable energy technologies in the electricity grid. In particular, for the grid operators, significant technical problems arise from successfully integrating renewable energy technology into the electricity network: first, the placement of power plants and, second, energy intermittency and its major effect on the electricity system. The unpredictability of wind power generation demands the employment of voltage control devices with very fast reaction times. The usage compared to conventional control methods of Flexible AC Transmission System (FACTS) devices is thus suggested. In some substations, the shutdown of power plants produces excess voltage. The placement of inductors at their connecting points might prevent this problem. These are activated when solar output is shut down (Ameur *et al.*, 2019). In comparison to gradual processes needed in developing and transforming existing power systems, renewable energy systems can be created on a big scale and connected to a grid over a relatively short period. There are several methods for increasing the flexibility of a power system, such as retrofitting existing coal-fired plants, constructing new pumped storage stations and gas-fired power plants, and using transregional power lines to provide energy supported in the neighboring power grids (Zhang *et al.*, 2018).

1.4 RENEWABLE ENERGY STORAGE TECHNOLOGIES

When the sun shines, solar power is accessible, and wind power is accessible when the wind blows. Furthermore, their production projection is subject to weather forecasting inaccuracies. As a result, to ensure good supply security in power networks with a growing RES share, a rising quantity of backup and balancing power capacity is necessary. In the electrical system, demand and supply must be balanced at all times. The system operator ensures that the quality of power is maintained while minimizing production costs. In other words, power plants are dispatched depending on their marginal costs; hence, the most expensive power plants are only employed to meet peak demand (peaker capacity). As a result, in spot electricity markets, spot prices reflect supply shortages. In the long term, if there are no capacity payment mechanisms, a power plant must charge rates above its marginal cost to meet its fixed expenses (Karhinen and Huuki, 2019). The key to resolving the renewable energy power generation process when it is discontinuous and intermittent is how to store renewable energy when it is not needed and release renewable energy when required. Liu and Liang Du (2020) create a set of evaluation criteria for renewable energy storage systems based on four dimensions: technological, economic, environmental, and social, as illustrated in Fig. 1.6. Storage capacity is the amount of energy available in the storage system once it has been charged. The quantity of energy stored in a given space or mass is referred to as energy density, whereas power density is the ratio of battery output power to weight. Response time describes the pace with which energy storage technology absorbs and releases energy, whereas lifetime denotes the cycle life of charge and discharge energy. Emissions

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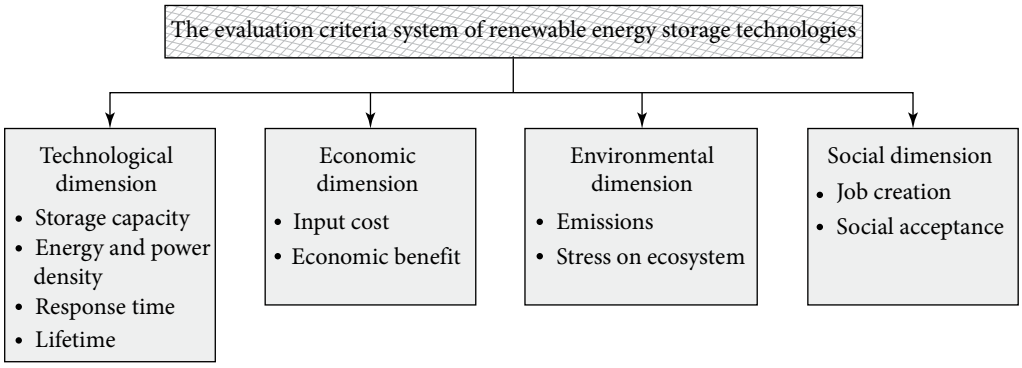

FIG. 1.6
The evaluation criteria of renewable energy storage technologies (Liu and Liang Du, 2020).

are the by-products of energy storage technology activities such as solid waste, wastewater, waste gas, etc. On the other hand, stress on the ecosystem indicates that the use of energy storage technology will consume a certain amount of land, vegetation, water resources, and so on and alter the original biological structure to some extent. As a result, it is critical to assess the friendliness of the ecological environment (Paster *et al.*, 2011).

For a range of applications in the power industry, electricity storage technology may be employed, from e-mobility and behind-of-meter applications to utility applications. For instance, utility-scale batteries can allow increased feed-in renewables to the grid through the storage of surplus production and the strengthening of renewable energy. Batteries also assist in delivering dependable and cheaper electricity to distant power networks and remote settlements, which otherwise rely on expensive imported diesel fuel for generating electricity, particularly when combined with renewable generators. At the moment, utility-scale stationary batteries are the most common kind of energy storage in the world. On the other hand, small-scale battery storage is anticipated to grow considerably by 2030, complementing utility-scale uses. Behind-the-meter (BTM) batteries are installed behind the utility meter of commercial, industrial, or residential users with the primary goal of lowering power bills. BTM battery installations are on the rise all over the world. Because of the expanding consumer market and the development of electric vehicles (EVs) and plug-in hybrid EVs, the cost of battery storage technology has decreased (International Renewable Energy Agency, 2019).

1.5 CONCLUSIONS

The global energy transition is underway, propelled by the dual imperatives of minimizing climate change and promoting long-term prosperity. Some of the major facilitators of this trend include

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an extraordinary drop in renewable energy costs, new potential in energy efficiency, digitalization, smart technology, and electrification solutions. At the same time, the energy transition must occur considerably more quickly. To fulfill global climate goals, renewable energy deployment must rise at least sixfold beyond existing government projections. This would require accelerating the tremendous progress that we are now seeing in the electricity sector, as well as considerably increasing efforts to decarbonize transportation and heating. By 2050, electricity should grow to approximately 50% in overall energy use. Two-thirds of energy consumption and 86% of electrical output would then be made up of renewables. The biggest proportion of the energy sector reduction required may be renewable electrical energy coupled with deep electricity that could lower CO_2 emissions by 60%. Today's decisions worldwide will be important to secure a sustainable future for energy and climate. The Sustainable Development Goals and the Paris Agreement provide a framework through which the global energy transition activities may be coordinated and expedited.

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CHAPTER

2 INTEGRATION OF RENEWABLE ENERGY SOURCES: A REVIEW OF HYBRID AND AGGREGATED ENERGY SYSTEMS

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2.1 INTRODUCTION

Renewable energy sources (RESs) have been continuously increasing their share in electricity production in the last few years due to environmentally oriented policies as a consequence of the concerns regarding the growth of greenhouse gas (GHG) emissions from fossil fuel exploitation. Moreover, several RES technologies in the last decade have reduced their investment cost considerably and are becoming mature from both a technological and a market perspective. This is particularly valid for solar photovoltaic (PV) panels (Kumar *et al.*, 2020), solar thermal (ST) panels (Tian and Zhao, 2013; and Fernández *et al.*, 2019), wind turbines (Manwell *et al.*, 2009), and biomass-fired power plants (Wegener *et al.*, 2018) [e.g., biomass-fired organic Rankine cycles (ORC)]. While hydroelectric power plants are of interest only for the power sector (owing to the required infrastructure and permits leading to high investment costs), these RES technologies are currently adopted in all sectors (residential, industrial, and tertiary). According to recent studies (IRENA, 2019), their Levelized Cost of Electricity (LCOE) is competitive with that of fossil-fueled technologies, prompting companies to make large investments. On the other hand, those with the lowest costs [i.e., wind and solar PV (IRENA, 2019)] are "intermittent RESs" featuring non-dispatchable power output. Also, their power output cannot be accurately predicted due to the uncertainty affecting wind speed and solar radiation. As far as wind

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energy is concerned, state-of-the-art forecast approaches achieve an error ranging from 10% to 20% of the installed power on a 24 h ahead forecast (Wu and Hong, 2007) and 10% for intraday 4h-ahead forecasts (Giebel *et al.*, 2011). A more accurate forecast can be made for PV production but the relative error still remains considerable (Shafiullah *et al.*, 2010; and Leva *et al.*, 2020).

These issues make solar PV and wind energy not suitable as stand-alone technologies for off-grid installations like islands and remote villages (Sanajaoba and Fernandez, 2016; and Moretti *et al.*, 2019). A large share of these intermittent renewables cannot be supported by electric grids either due to the issues of power quality (voltage and frequency control, harmonics reduction, etc.) (Shafiullah *et al.*, 2010). The problems caused by the intermittency of the power output can be smoothed by integrating non-dispatchable RESs with energy storage systems (e.g., batteries) and/or different types of RESs as well as dispatchable power generation units. These aggregated energy systems are gaining considerable interest and, depending on the application, are called by different names: "virtual power plants" (Pandžić *et al.*, 2013), "microgrids" (Fathima *et al.*, 2018), "multi-energy systems" (Dincer and Zamfirescu, 2014; and Zatti *et al.*, 2019a), and "energy districts" (Zatti *et al.*, 2017; and Mohammadi *et al.*, 2018). The definition of such aggregated systems with the most interesting examples are reported in Sec. 2.2. It is worth noting that in these aggregated systems, the integration occurs only at the "network level," which sums the power (electric and thermal) generated by the different energy technologies (PV, wind, battery, etc.). Each energy unit preserves the same efficiency and input/output flows as a stand-alone operation. A gain in dispatchability and operational flexibility is obtained by optimizing the sizing of the units (design problem) and the management of the energy flows (operational problem). Section 2.2.1 reports a brief review of the approaches developed for this task.

Different RESs can be integrated also at a "technological level" by modifying the energy conversion processes. This kind of integration, called "hybridization," is aimed at increasing energy efficiency and operability and/or decreasing costs. Examples of hybrid power plants are reported in Sec. 2.3.

2.2 AGGREGATED ENERGY SYSTEMS

Renewable energy production is strictly dependent on the weather forecasts (PV and wind) or the availability of the natural resources on which they are based (water, geothermal power, and biomass feedstock) and cannot be planned as conventional power generation. This limitation can be overcome by considering a power grid or microgrid constituted by the integration of multiple RES plants and storage systems. The interest in such hybrid systems is continuously growing since it is a very promising way to enhance the overall system dispatchability by exploiting synergies and complementary behaviors (e.g., PV and wind) of various technologies, it is possible to provide a constant supply of power and avoid power imbalances in the national grid, which can be operated safely, even with a large share of RES.

The benefits of RES aggregation are multiple and do not only concern the grid stability issue: many studies report that hybrid systems perform better both from the economic and technical standpoints.

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The integration of several technologies into a single hub results in (i) a lower cost of energy (i.e., LCOE), (ii) higher number of operating hours (i.e., capacity factor), (iii) higher system efficiency, (iv) lower costs by sharing technologies such as system balance of plants, utilities, buildings, cooling system, and personnel and, when present, (v) in a reduced storage system size (Paska *et al.*, 2009).

The following terms are used to denote aggregated energy systems:

- "Virtual Power Plants" (VPPs) (Pandžić *et al.*, 2013): A set of power generation units that are virtually aggregated and operate in the electricity markets as a single power generation unit, but the units remain independent in their operation and ownership. The advantage of a Virtual Power Plant is the capability of distributing the power generated by the individual units during periods of RES over-production or under-production. This allows smoothing the unbalances of import/export power from/to the electric grid.
- "Microgrids" (Fathima *et al.*, 2018): A set of power generation units, electric energy storage, and users interconnected by a local electric grid. The microgrid can be disconnected from the main national electric grid and operate "on island" (also called "off-grid" operation). Compared to VPP, it features distributed users to be served and a local electricity distribution network. Typically, microgrids are used in remote villages (Ferrer-Martí *et al.*, 2013; and Moretti *et al.*, 2019), small islands (Hatziargyriou *et al.*, 2020), and large boats (Jayasinghe *et al.*, 2017).
- "Multi-energy systems" (MESs) (Dincer and Zamfirescu, 2014; and Zatti *et al.*, 2019b): Energy systems comprising multiple types of energy conversion units that use different forms of primary energy and generate different forms of useful energy vectors (electricity, heating, cooling, etc.). The different energy conversion units are interconnected by thermal and electric networks and the system can include energy storage systems.
- "Energy districts" (Zatti *et al.*, 2017) and "Positive Energy Districts" (PEDs) (Mohammadi *et al.*, 2018): An energy district is an area with defined borders, consisting of interconnected buildings, with an energy demand covered by on-site renewable energy sources and distributed energy conversion systems. PEDs are energy districts with a positive overall yearly energy balance.

Figure 2.1 summarizes the four main concepts of aggregated energy systems. In all aggregated energy systems, an Energy Management System (EMS) tool is adopted to optimize the load and on/off operation of the units.

Given the multiple operational degrees of freedom offered by aggregated energy systems, it is important to develop effective EMSs in order to exploit the synergies between the different units. Given the forecasts on energy production from intermittent RESs, the forecast of energy demand, and the forecasts of energy prices, the EMS determines the optimal on/off schedule and loads of units. State-of-the-art EMS tools employ linearization techniques (Bischi *et al.*, 2014) to reformulate the problem as a Mixed Integer Linear Program (MILP), which can be solved to global optimality using commercially available solvers (Moretti *et al.*, 2021). Current research on EMS is focusing on approaches to handle forecast uncertainty so as to determine a "robust" operational solution (Moretti *et al.*, 2020). It is worth

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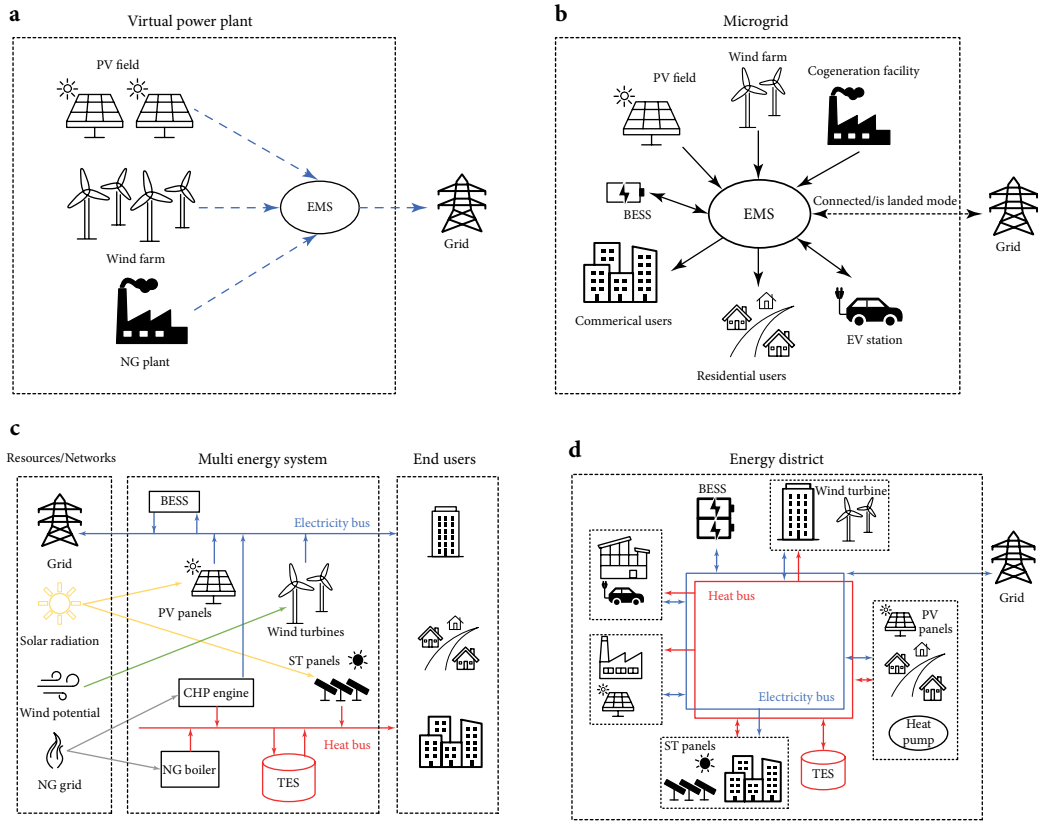

FIG. 2.1
Example of the architecture of VPP (a), microgrid (b), MES (c), and energy district (d).

noting that also the design of aggregated systems requires *ad hoc* optimization approaches, taking into account the expected operation of the system across its lifetime (Ferrer-Martí *et al.*, 2013; and Klemm and Vennemann, 2021).

2.2.1 Aggregated PV-BESS systems

A very promising coupling architecture, widely adopted today, is based on the combination of the PV system with a Battery Energy Storage System (BESS). This can be done for several reasons (i) to minimize the energy curtailed and maximize the energy self-consumed or injected into the grid, (ii) to increase the level of dispatch and the reliability of power supply provided by the systems, and,

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eventually, (iii) to provide ancillary services to the electricity grid such as peak shaving, load shifting, demand side management, frequency and voltage control, and reserve power.

Al-Khori *et al.* (2021) performed a techno-economic analysis of a 33.5 MWe PV plant with a large battery stack (210 MWh) to continuously provide power supply to an industrial facility. A LCOE of 130 €/MWh was found. Khawaja *et al.* (2017) presented a sizing procedure to find the best cost configuration for grid-connected PV-BESS systems for several battery types. The proposed system allows increasing the share of self-consumed energy (75%) with respect to the use of the PV system alone (48%). Moreover, for a battery size of 1 MWh, the optimal PV size was found to be 710 kWe featuring an LCOE value from 132 €/MWh for redox-flow up to 156 €/MWh for lithium-ion battery type.

These configurations are particularly suited also for off-grid small islanded systems and household applications. Here, rather than provide a stable power output, the PV-BESS system is aimed at increasing self-consumption and lowering the energy purchased from the grid. A comprehensive study on these systems can be found in Quoilin *et al.* (2016), where the level of self-consumption achievable by a PV-BESS household system with and without batteries, for several sizes, was evaluated. They notice that achieving full off-grid operation would lead to an excessive oversizing of the system.

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2.2.2 Aggregated solar–wind systems

An example of a hybrid architecture commonly adopted to overcome the intermittency of a single renewable source is constituted by the combination of solar and wind technology. While solar radiation first increases and then decreases along the day, with a peak occurring around midday, in contrast, wind intensity is typically much less correlated with time of day and can be even higher at night (Dykes *et al.*, 2020), resulting in an overall compensation of a possible hybrid system output.

A good matching between solar and wind availability could occur not only on a daily timescale but it could also be observed at a seasonal level; for example, for the eastern one-third of the United States, maximum wind speeds occur during the winter and early spring while minima occur in the summer, which is when solar radiation is stronger (Manwell *et al.*, 2010). Thus, exploiting the natural compensation of solar and wind resources, a hybrid system not only reduces the randomness of the generation but also reduces the overall system size and, therefore, reduction in capital expenditures is achieved.

However, even if PV and wind are mature technology from the technical and the market standpoint, their integration sometimes is not enough to guarantee a good quality of supply and is still challenging to operate the system, avoiding energy fluctuations and imbalances between supply and demand that may result in production curtailment. In order to increase system dispatchability and make it more controllable, energy storage and/or a backup generator can be included. With these addictions, a further system size reduction and better quality or smoother energy production are achieved (Al Badwawi

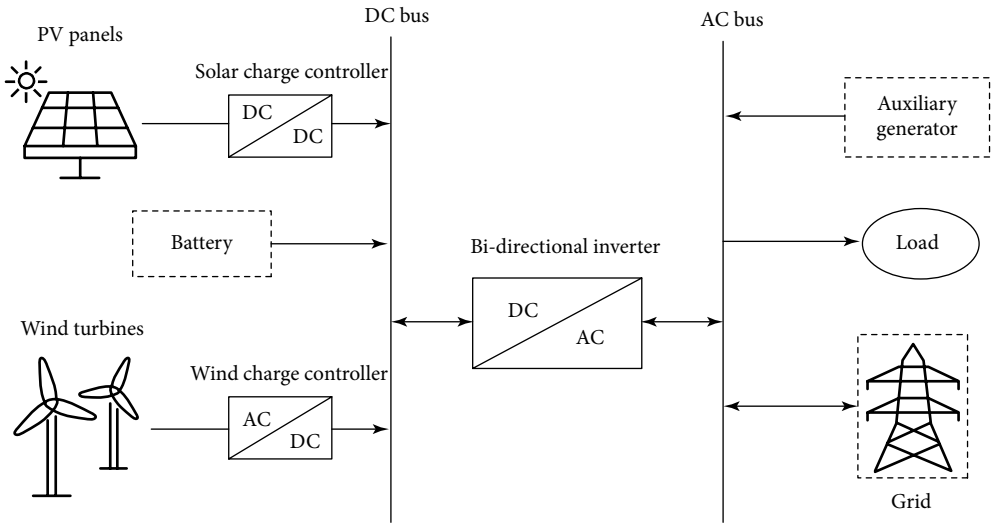

FIG. 2.2
Scheme of a wind–solar aggregated energy system (grid-level integration) with optional BESS.

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et al., 2015). The scheme of the typical arrangement of aggregated PV–wind systems with BESS is shown in Fig. 2.2.

Sanajaoba and Fernandez (2016) implemented a mathematical model aiming at minimizing total system cost to design a stand-alone hybrid system for seven unelectrified villages located in India. They considered the load changes with seasons and tested different hybrid combinations: PV-BESS, wind-BESS, and PV-wind-BESS. The simulation results revealed that the integration of PV and wind drastically reduced the battery storage requirements compared to PV-BESS and wind-BESS systems only.

Becker *et al.* (2014) investigated the optimal mix of regional wind and solar production in several United States locations with the aim of minimizing storage, balancing energy, and LCOE. They found that on a daily timescale, the optimal matching between generation and load occurs at about 80% wind share in the mix due to the night gap in solar production. Going from solar only to this mix reduces backup energy needs by up to 50%. They also found that LCOE and optimal mix may vary significantly with the region considered.

2.2.3 Aggregated wind–PHS systems

As the RES penetration in the national or in a microgrid becomes more relevant, the integration is made much more difficult by the dynamic behavior of renewables, which may cause safety and reliability

issues to the power systems. In this context, Pumped Hydrostorage (PHS) has been considered an effective energy storage solution due to the large energy density and ability to buffer intermittencies caused by high variability of RES or to compensate for large variations in generation or supply (Rehman *et al.*, 2015; and Javed *et al.*, 2020). Pumped hydrostorage plants store energy in the form of the potential energy of water using a system of two reservoirs at different elevations connected by one (in the case of reversible pump-turbine) or two penstocks (Rehman *et al.*, 2015). Water is pumped to the upper reservoir when there is surplus energy while in times of excess demand, water from the upper reservoir is released and electricity is generated through a hydraulic turbine.

Thus, coupling PHS with wind generation can significantly reduce the curtailment rate at which wind power plants alone currently operate. By exploiting the particular capacity of PHS to fast start and stop whenever required and its flexibility to adapt to sudden load and supply variations and perform load following for several hours due to its high energy densities, it is possible to greatly increase the wind penetration potential not only in the main grid but also in stand-alone systems and islanded areas (Segurado *et al.*, 2016).

The main reasons for encouraging the hybridization of wind and PHS systems are (i) it allows large wind penetration rates, (ii) maximizes the production and minimizes the loss in terms of energy (i.e., wind curtailment), and (iii) reduces system costs with respect to their stand-alone configurations.

In the literature, the main focus of wind–PHS studies is related to the optimal management of such systems, which are able to guarantee feasible scheduling while respecting reliability and stability constraints on the system and grid operation. There is wide variability in the literature on the main technical and economic indicators of wind–PHS systems, according to the geographical location, size, elevation, and subsidies considered with LCOE ranging from 44 up to 276 $/MWh (Canales *et al.*, 2015).

Canales *et al.* (2015) compared the operation of a wind hydrohybrid system associated first with a conventional reservoir and then with a PHS plant, finding that the latter has a 33% higher initial capital cost, but after 20 years of system operation, the operation cost will be just 47% of conventional power systems due to fuel savings and lower emissions.

2.2.4 Aggregated solar–PHS systems

While solar energy is widely known to be less intermittent compared to the wind, it is only available during the day. Hence, in order to provide a smooth and constant output, it can be combined with an energy storage system such as PHS (several energy storages devices are discussed in the literature to enhance the reliability of the system when solar is the only primary source of energy, i.e., battery, fuel cell, PHS, flywheel, and compressed air energy storage), which is able to store a considerable amount of energy and give it back when needed. A possible solar–PHS hybrid configuration with a reversible pump-turbine is shown in Fig. 2.3. A common operational strategy is to use the energy produced by the PV array to meet the load demand when available while storing the surplus (if any) with the PHS. The

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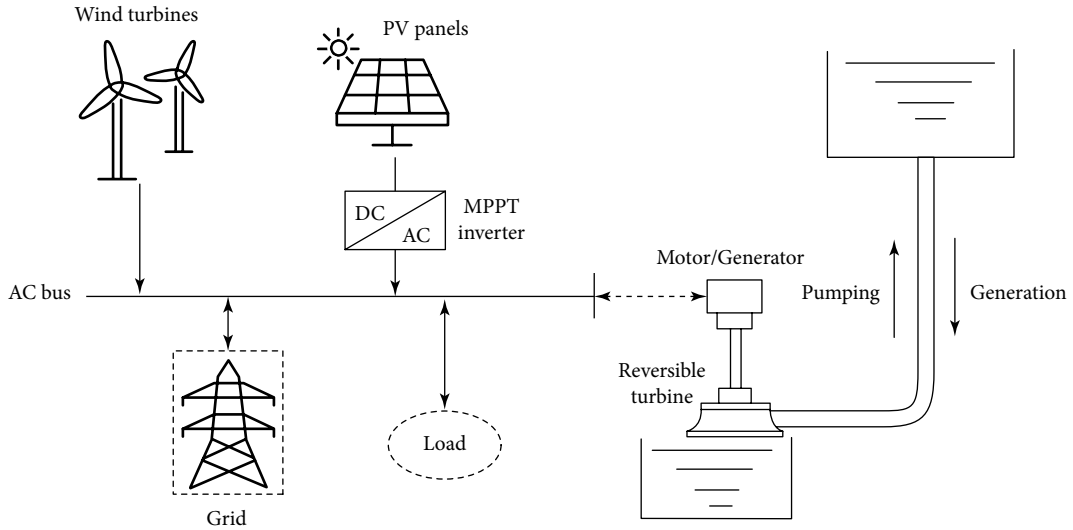

FIG. 2.3
Conceptual schematic design of an aggregated PV–wind turbine–PHS system (grid-level integration).

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energy stored will be then released at night or during daytime periods with insufficient solar radiation. By doing so, the system is able to reduce its energy losses and maximize energy production, mitigating RES variability and increasing system reliability.

A PHS solution for microgrid PV systems for a remote island was investigated by Ma *et al.* (2015). As optimization criteria for the sizing of the system, the cost of energy and the Loss of Power Supply Probability (LPSP), which is a measure of power supply reliability, were chosen. A GA approach is used to tackle the multi-objective optimization problem. According to the Pareto optimal solution, if a small proportion of unserved load can be accepted (5% LPSP), significant reduction in the PV size and thus capital costs can be achieved.

Another study on a stand-alone PV–PHS power system (Shabani and Mahmoudimehr, 2018) carried out an optimal design of the hybrid plant for the different types of PV tracking technologies with a multi-objective optimization algorithm that considers the investment cost and loss of LPSP as objective functions. The comparison between the optimal design of PV–PHS and PV–battery systems revealed that although the PV–battery system can reach higher yearly round-trip efficiency and thus led to a lower size of PV field, it has also a higher investment cost and environmental impact of battery disposal.

2.2.5 Aggregated PV–CSP systems

The aggregation of concentrated PV and Concentrated Solar Power (CSP) plants could lead to several advantages, as the result of the combination of two mature and promising solar technologies. For instance, adding a PV system to a CSP plant allows thermal energy to be stored while the PV produces power during the day, and then it can be released at night to generate electricity in a power block section, even in the absence of solar radiation. Conversely, when the direct solar radiation is not sufficient to directly feed the CSP plant (e.g., cloudy days), the plant will still be able to produce some useful power because of the capacity of PV panels to exploit the indirect and diffuse radiation. Finally, the probability of PV-caused imbalances can be reduced by the power section of the CSP plants, which relies on a well-proven conventional technology such as steam or an ORC cycle for the power generation.

In the literature and at a market level different architectures and configurations of grid-level aggregated PV–CSP plants exist. The integration may be "partial" if the CSP and PV systems are operated independently, while it is said to be "full" when the two systems operate simultaneously to supply the required power output with a joined control system (EMS) to optimize the shares of CSP and PV production. Examples of grid-level "fully-integrated" CSP–PV hybrid power plants are the recently built Cerro Dominador in northern Chile (Green *et al.*, 2015), the Ottana CSP–PV pilot power plant (Petrollese *et al.*, 2020), and the Partanna small-scale CSP–PV hybrid systems (Falchetta *et al.*, 2020).

The Ottana solar facility, located in Sardinia (Italy), is able to generate 630 and 400 kW of electricity through the CSP and the PV technology, respectively. The CSP section is based on linear Fresnel collectors using thermal oil as heat transfer fluid (HTF) and a two-tank direct Thermal Energy Storage (TES) system with approximately 5 h of storage capacity while the power is produced by an ORC unit employing hexamethyldisiloxane as working fluid.

The Partanna CSP–PV plant, located in Sicily (Italy), has a total installed capacity of 4.3 MWe and is able to provide 15 h of operation at full load. The CSP field is based on linear collectors (Fresnel type) and employs molten salts as working fluid, whereas a conventional steam cycle is used for power generation.

Finally, the Cerro Dominador facility in Chile's Atacama Desert is an example of a large hybrid solar plant that combines a 110 MWe steam cycle based on molten salt tower CSP technology with a 100 MWe PV plant. With almost 18 h of thermal energy storage, it can supply clean and stable energy for most of the year. In Green *et al.* (2015) the operation of the Cerro Dominador plant was analyzed reporting that if the CSP plant is dispatched in response to the output from the PV plant, the capacity factor of the PV–CSP hybrid system can reach values in the range of 80%–90%, much higher than that of conventional CSP plants (between 20% and 50%) and comparable to conventional thermal power plants.

Further improvements in dispatchability can be achieved using technology-level integrated CSP–PV systems, as described in Sec. 2.3.1.

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2.2.6 Aggregated PV–geothermal

While the solar resource is mainly available during daily hours, the geothermal heat is almost present at a constant rate during the whole day, since it is not affected by external weather conditions (DiPippo, 2005). An interesting solution to exploit the combination of solar and geothermal resources is to add a PV field to an existing geothermal plant to increase the energy output in the peak hours of power demand, which usually coincide with the hours where the solar radiation is more intense.

The PV system not only will act as a boost for the energy production during the daytime but also will complement the geothermal plant output degradation during hot summer temperatures when geothermal plant output is affected by the increased ambient temperature in the air-cooled condenser (Dimarzio *et al.*, 2015). A similar result was found in (Li *et al.*, 2020), where the possibility of powering the pump station of The Geysers geothermal field (California) with PV arrays was investigated.

2.2.7 Aggregated wind–biomass

A way to mitigate the wind power intermittency without resorting to conventional technologies can be achieved by aggregating biomass-fired plants with wind farms. By using a biomass system as a backup generator, the impact of forecasting error can be reduced, provided an accurate choice of the biomass fuel that should always be available (i.e., not seasonal) and easy to manage and store.

Pérez-Navarro *et al.* (2010) investigated a system composed of a biomass gasifier and an internal combustion engine to compensate for the variations coming from a 40 MWe of a wind park in the neighborhoods. A methodology for the derivation of the design parameters and sizing of the system was proposed. The biomass-fired plant, which features a nominal power of 4.5 MWe, was effectively able to compensate the imbalances for most of the wind farm operating hours (almost 90%).

2.2.8 Multi-energy systems

Multi-energy systems are typically used to supply electricity and heating/cooling to buildings, city districts, and industrial facilities (Gabrielli *et al.*, 2018; and Zatti *et al.*, 2019a). These systems aggregate one or more renewable energy sources with energy storage systems and conventional energy conversion technologies (e.g., heat pumps and CHP engines) (Pinamonti and Baggio, 2020). The aggregated energy system is designed and operated with the aim of minimizing the cost and/or the primary energy consumption and/or the CO_2 emissions.

One of the simplest and most common types of MESs for small-medium size grid-connected European buildings includes PV panels, a heat pump, an optional heat storage tank, and an optional battery (Pinamonti and Baggio, 2020). Depending on the PV sizing criteria, these systems can cover the whole building's annual energy consumption leading to near-zero net CO_2 emissions (Wei and Skye, 2021). On the other hand, in lack of BESSs, large diffusion of these systems causes significant control issues to the medium and low voltage distribution networks as shown in Delfanti *et al.* (2010). The

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commercialization of such PV-based systems has been favored by the massive incentive programs granted by European governments. According to one of the latest cost references (Lazard, 2020), in regions with mid irradiance, the LCOE of stand-alone PV rooftop panels (<10 kW) is in the range of 123–186 €/MWh while the LCOE of integrated systems PV-BESS can be even higher. The high LCOE indicates the need for subsidies, especially, for the installation of BESSs.

Another simple type of MES for buildings is based on ST panels, a thermal storage system, and a boiler or heat pump (Mavromatidis and Petkov, 2021).

For districts of buildings served by district heating/cooling networks, the installation area available for PV panels would not be sufficient to cover the electricity and heating demand. For this reason, PV panels and heat pumps are typically aggregated with gas-fired boilers and CHP engines (Zatti *et al.*, 2019b).

Gabrielli *et al.* (2018) studied the optimal design of MESs for an urban district. The candidate units are shown in Fig. 2.4. The design of the system is optimized using a MILP formulation for different levels of annual CO_2 emission targets. Results indicate that, why PV panels are always economically optimal, ST panels, the seasonal storage system, and the power to the gas system are selected only for tight targets of annual CO_2 emissions.

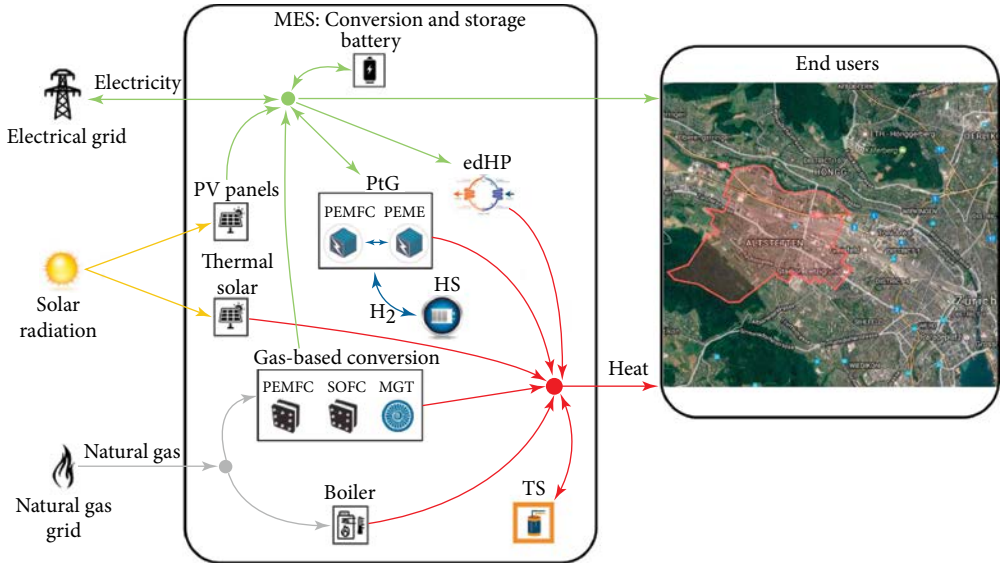

FIG. 2.4
Scheme of the MES studied by Gabrielli *et al.* (2018) for an urban district. Reproduced from Gabrielli *et al.*, Appl. Energy **219**, 408–424 (2018). Copyright 2018 Author(s), licensed under a Creative Commons Attribution 4.0 License.

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Martelli *et al.* (2020) optimized the design and operation of the MES serving four different urban districts. The results indicate that the optimal system design depends on the features of the energy demand (heat to power ratio and available area for solar panels) and the target of CO_2 emission reduction. In general, the system opts for installing a biomass-fired ORC together with, usually, PV and, when possible, an absorption chiller and heat storage.

2.3 HYBRID ENERGY SYSTEMS (TECHNOLOGY-LEVEL INTEGRATION)

Different from aggregated energy systems, in hybrid systems, the efficiencies of the different units are mutually influenced because their energy conversion processes are tightly integrated. The main goals of making such right integration are

- increasing the efficiency of the energy conversion process,
- decreasing the specific capital cost of the integrated system, and
- increasing the operational flexibility (maximum ramping rates, etc.) and dispatchability of the output power.

Technologies based on thermodynamic cycles, such as Rankine cycles, are well suited for hybridization since they can be arranged to recover heat from several primary energy sources. Sections 2.3.1–2.3.4 describe the most interesting examples of hybrid renewable-based plants reported in the literature.

2.3.1 Hybrid solar CSP–PV

Hybrid CSP–PV plants are the result of the hybridization between CSP and PV, the two leading technologies for electricity production from solar energy. Since the CSP technology is equipped with a Thermal Energy Storage (TES), the excess energy of the PV field can be converted into heat and then stored in the form of thermal energy in a hybrid CSP–PV configuration. Further, the combined system can take advantage of the good dispatchability of the CSP technology and its output characteristic curve, providing better power quality and reducing the impact of the PV fluctuations in the grid. Thanks to the integration, the hybrid CSP–PV plants are able to fully exploit the solar radiation (direct normal and global horizontal irradiation contributions), leading to better generation efficiency and to a reduced cost of energy (LCOE) (Fig. 2.5).

The most straightforward way to enable an energy transfer is to include an Electric Heater (EH), i.e., an electric resistance, to convert some of the PV output power into heat to be transferred to the hot Heat Transfer Fluid (HTF). It must be noted that this transfer still represents a form of energy degradation, but it is a very simple and economic solution. Compared to grid-level aggregated CSP–PV plants (Sec. 2.5), it allows smoothing the PV production peaks and using such energy in the subsequent hours of the day when the direct solar radiation is lower.

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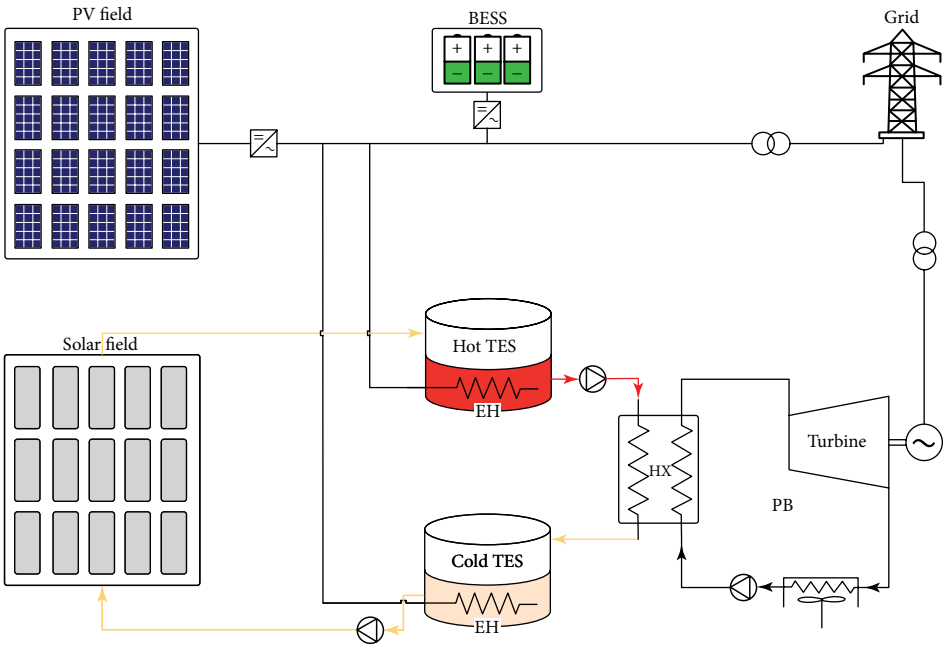

FIG. 2.5
Conceptual schematic design of hybrid PV–CSP system with electric resistance in the hot and cold thermal energy storages.

Hlusiak (2014) performed a techno-economic assessment of a flat PV–CSP hybrid system with TES with a simulation model based on the meteorological data of Morocco. The results of the analysis showed that the PV–CSP hybrid plant is a viable option to provide electricity following the national electricity demand. Compared with a CSP-alone plant with TES, the LCOE of the PV–CSP hybrid plant can be decreased by 8%–13%, ranging from 130 to 183 €/MWh. The LCOE may be further reduced to 88–108 €/MWh, when the hybrid plant is combined with wind power and batteries.

In Starke *et al.* (2018), the design and sizing problem of a hybrid CSP–PV system was tackled via a multi-objective optimization methodology based on the implementation of a transient simulation model, coupled with an evolutionary optimization algorithm to address the tradeoff between the costs and the plant dispatchability. Results show that the capacity factor achieves values higher than 85%, and the LCOE is lower than those observed for stand-alone CSP plants.

2.3.2 Hybrid CSP–geothermal systems

Many areas spread around the world show a good match between the availability of solar surface radiation and a good geothermal gradient (Li *et al.*, 2020). For this reason, hybrid solar and geothermal

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power systems are known to be an interesting combination of RES that mutually benefits the common features of solar and geothermal energy. The basic idea is to combine an existing or new geothermal plant with the technology of solar collectors used in CSP plants utilized in parallel in order to increase the heat transferred to the working fluid. Multiple configurations are possible, both for the choice of the geothermal plant (single flash, double flash, or binary plants) and the solar collector's type (parabolic or linear). Many geothermal resources can provide a geothermal fluid in a limited range of temperatures (150 °C or less) and the solar collector technology be used to superheating the geothermal fluid, with an overall increase in the turbine inlet temperature and, thus, in the cycle efficiency. When coupled with CSP collectors, the geothermal fluid might serve also as storage for solar energy, increasing the overall system dispatchability (Fig. 2.6).

A typical architecture is shown in Fig. 2.6, where two modes of operation for the hybrid plant are shown. At nighttime or more generally when the solar resource and the electricity demand are low, the plant runs in a full-geothermal configuration since all the heat to the working fluid is provided by the geothermal brine. During the peak periods of electricity demand, instead, only part of the heat is supplied to the working fluid with the geothermal fluid and the remaining part is provided by an additional heat

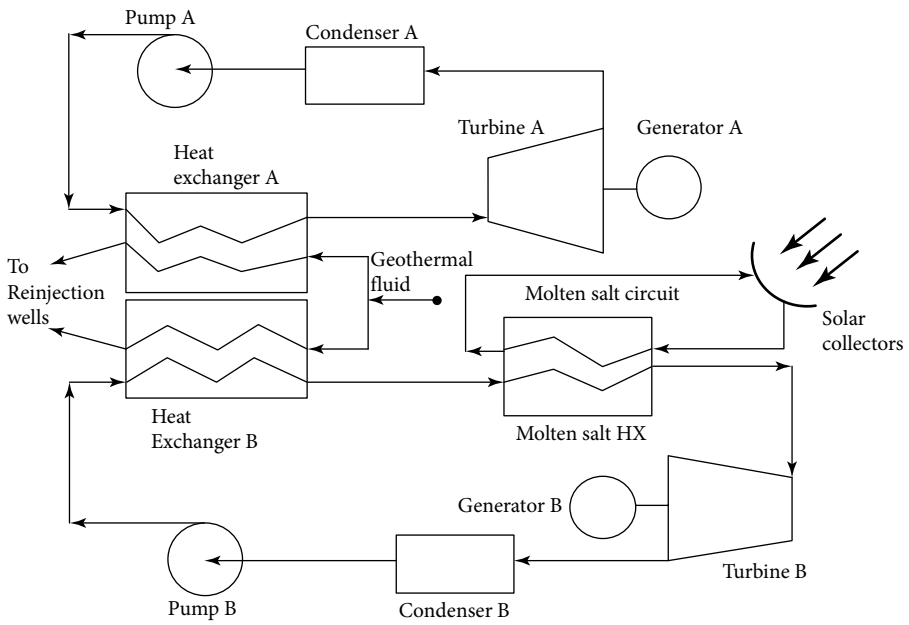

FIG. 2.6
Example of hybrid geothermal–Solar System with geothermal source and CSP in series proposed in Bokelman *et al.* (2020). Reproduced with permission from Bokelman *et al.*, Energies **13**(5), 1018 (2020). Copyright 2020 Author(s), licensed under a Creative Commons Attribution 4.0 License.

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exchanger fed with the HTF coming from the solar field, with the aim to provide the heat of superheating to the working fluid before it enters the turbine and thus to increase the plant output.

Ghasemi *et al.* (2014) designed a model to hybridize an existing ORC geothermal power system with a low-temperature solar trough facility to enable a better extraction of geothermal energy. In particular, the solar field works in parallel with the geothermal system to vaporize part of the working fluid. A boost in annual power generation of 5.5% was obtained and a 17.9% increment in efficiency compared to the stand-alone geothermal and solar systems was observed. In another work (Ayub *et al.*, 2015), the hybrid system developed by Ghasemi *et al.* (2014) was compared with an optimized stand-alone geothermal system and a detailed economic analysis, including the capital, maintenance, and operation costs, was conducted for both plants, reporting a 2% decrease in the LCOE attributable to the hybrid system. Astolfi *et al.* (2011) evaluated the potential of a solar-hybrid geothermal plant based on an ORC cycle finding a cost reduction of 50% compared to stand-alone systems.

2.3.3 Hybrid geothermal–biomass systems

A similar way to provide additional heat or increase the energy value of the working fluid in geothermal plants is by means of a biomass-fired superheater. With this hybrid configuration it is possible to adjust the biomass flow rate in order to maximize the net electric power or the thermodynamic efficiency of the plant that will change during the year because of variation in ambient air and geothermal fluid temperatures (Briola *et al.*, 2019).

Thain and DiPippo (2015) studied the retrofit of an existing geothermal plant with the addition of a biomass-fired boiler. A 32% gain in the power output, but a decrease in the second law efficiency of the hybrid plant were found.

Briola *et al.* (2019) analyzed the feasibility of a novel configuration of a hybrid binary geothermal biomass power plant air-cooled (the ORC cycle receives also the heat of the biomass boiler). The results of the study indicate that the presence of the biomass source mitigate the negative effects produced by the degradation of the reservoir temperature during the plant life and the seasonal changes in ambient temperature.

2.3.4 Hybrid solar–biomass systems

Solar–biomass hybrids are also an interesting viable option in those regions where solar radiation is limited but biomass resources are readily available. They couple the CSP technology for power production with an auxiliary boiler fed by biomass used to increase the heat content of the heat transfer fluid coming from the field or to super or re-heat the generated steam before going to the turbine section (Fig. 2.7).

Hybridization is aimed at enhancing the dispatchability of the plant: when solar radiation is available, biomass use is limited; then, when solar radiation is not enough to guarantee a constant plant operation,

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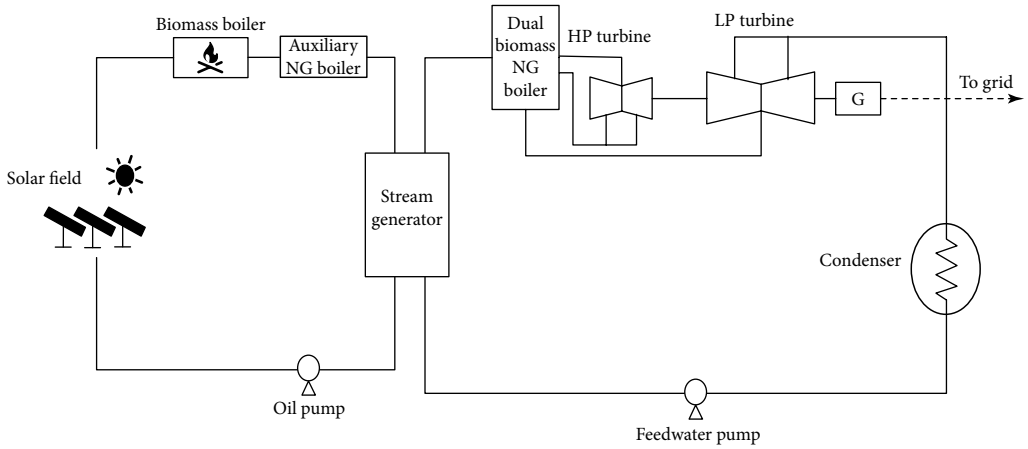

FIG. 2.7
Scheme of the thermosolar Borges hybrid solar–biomass plant (Spain).

biomass is fired in the boilers. Several arrangements are possible for the CSP configuration: parabolic trough is a mature technology showing good hybridization performances but is penalized by seasonal variability, which requires greater biomass feed in winter. Linear Fresnel collectors, instead, due to their high efficiency over the midday period, can be used for solar field direct steam generation, which makes it an alternative hybridization option (Hussain *et al.*, 2017). Finally, because of the complex operation and high land use factor, solar tower technology is less appealing for hybrid plants, especially considering the small size typical of these systems.

Nixon *et al.* (2012) assessed the feasibility of hybrid solar–biomass power plants in India for various applications (tri-generation, electricity generation, and process heat) and for different plant sizes with peak thermal capacities ranging from 2 to 10 MWt. In comparison to biomass-only, the hybrid operation saves up to 29% biomass and land and is able to achieve an LCOE in the range of other renewable technology such as solar and wind, though it is still high if compared with conventional power plants.

In Hussain *et al.* (2017), a technical and economical assessment regarding the viability of a CSP and biomass hybrid as an alternative to conventional fossil-fueled power plants. They reported that hybridization has a positive effect both on the power plant dispatchability and biomass consumption.

2.4 CONCLUSIONS

Hybrid and aggregated energy systems represent a promising way to integrate different renewable sources since they feature a more reliable (dispatchable) power output and more favorable costs. Indeed, several options have been studied, and today, they are available in the market. Table 2.1 summarizes

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Table 2.1

Summary of the hybrid and aggregated renewable-based energy systems available in the literature. The diagonal elements of the matrix denote non-hybrid systems. Since the matrix is symmetric, cells below the diagonal are not filled.

RES technology	Solar PV	Solar CSP	ST panels	Wind	Geothermal	Hydro PHS	Biomass
Solar PV	PV plant (Kumar *et al.*, 2020) PV + BESS (Quoilin *et al.*, 2016; Khawaja *et al.*, 2017; and Al-Khori *et al.*, 2021)	Aggregated PV–CSP (Falchetta *et al.*, 2020; and Petrollese *et al.*, 2020) Hybrid CSP–PV (Hlusiak, 2014; and Starke *et al.*, 2018)	MES (Gabrielli *et al.*, 2018; Zatti *et al.*, 2019a,2019b) Hybrid PVT (Tian and Zhao, 2013)	Aggregated PV–wind (Becker *et al.*, 2014; and Sanajaoba and Fernandez, 2016)	Aggregated PV–geothermal (Dimarzio *et al.*, 2015; and Li *et al.*, 2020)	Aggregated PV–PHS (Ma *et al.*, 2015; Shabani and Mahmoudimehr, 2018; and Javed *et al.*, 2020)	MES (Mavromatidis and Petkov, 2021) PV–biomass hybrid (Hussain *et al.*, 2017)
Solar CSP		CSP plants (Fernández *et al.*, 2019)	n.a.	n.a.	CSP–geothermal hybrid (Astolfi *et al.*, 2011; and Ghasemi *et al.*, 2014)	n.a.	CSP–biomass hybrid (Nixon *et al.*, 2012; and Hussain *et al.*, 2017)
ST panels			Solar thermal panels (Tian and Zhao, 2013)	n.a.	n.a.	n.a	MES
Wind				Wind turbines (Manwell *et al.*, 2009)	n.a.	Wind–PHS (Canales *et al.*, 2015; Segurado *et al.*, 2016; and Javed *et al.*, 2020)	Aggregated wind–Biomass (Pérez-Navarro *et al.*, 2010)
Geothermal					Geothermal power plants (DiPippo, 2005)	n.a.	Geothermal–biomass hybrid (Thain and Dipippo, 2015; and Briola *et al.*, 2019)
Hydro PHS						PHS plants (Rehman *et al.*, 2015)	n.a.
Biomass							Biomass-fired plants (Wegener *et al.*, 2018)

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the aggregated and hybrid renewable-based systems studied in the literature. They are classified on the basis of the two main renewable energy technologies adopted. Looking at the matrix, it is evident that the most studied and interesting integrated systems combine either two intermittent sources (e.g., wind and solar), one intermittent and one dispatchable/constant (e.g., solar and geothermal or solar and solar and geothermal), and one intermittent and one with storage capacity (e.g., concentrated solar with thermal storage and PV and PV and pumped-hydrostorage plants). Integrated systems using either solar PV or wind are the most studied because of the more favorable economy of these technologies (i.e., lowest cost of electricity). Among these technologies, grid-level aggregated PV–wind systems turn out to be more studied and widely used in practice, especially in microgrids with energy storage systems, to provide power to remote villages and islands. The current trend is to use these aggregated systems as virtual power plants to provide balancing services to the electricity grid. The continuous cost reduction of batteries is progressively making these aggregated solutions cost-competitive with conventional dispatchable power production technologies. Where possible, the storage capacity can be provided by pumped-hydrostorage power plants. Aggregating several renewable energy sources is advantageous also for energy districts that require electricity, heating, and cooling. Hybrid systems, featuring integration between the different energy conversion technologies, may offer considerable operational and efficiency advantages compared to grid-level aggregated systems, but they are still in the development stage. Although several papers investigated hybrid systems such as CSP–PV, CSP–geothermal, and CSP–biomass systems plants, further research, development, and testing are required. Among these hybrid options, the most studied are based on concentrated solar power plants: hybrid CSP–PV systems and hybrid CSP–geothermal systems.

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CHAPTER

3 RENEWABLE ENERGY TRADE

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3.1 INTRODUCTION

The International Energy Outlook (Conti *et al.*, 2016) indicates that global energy-induced CO_2 emissions would increase up to 7.6% in 2040. These projections suggest that ascending emissions are highly sensitive in developed nations, which depend on fossil fuels to boost economic growth (Lin and Wang, 2019). The awareness of environmental problems is relatively recent in the economic literature (Grossman and Krueger, 2019; and Meadows *et al.*, 2019). In the early 1990s, the empirical hypothesis of the Environmental Kuznets Curve (EKC) provided empirical evidence connecting economic growth and environmental degradation (Selden and Song, 1994; Grossman and Krueger, 2019; and Shafik and Bandyopadhyay, 2019). More recent studies amplified this primary model, exploring additional driving forces of environmental degradation, e.g., energy innovation, FDI, energy use, international tourism, trade openness (Andreoni and Levinson, 1998; Andreoni and Levinson, 2001; Popp, 2002; Jaffe *et al.*, 2005; Wang, 2005; Aghion *et al.*, 2014; Álvarez-Herranz and Balsalobre-Lorente, 2015; Balsalobre-Lorente and Alvarez-Herranz, 2016; Álvarez-Herranz *et al.*, 2017; Sinha *et al.*, 2018; and Shafik and Bandyopadhyay, 2019).

Even the share of fossil sources is still critical; the energy mix has been altered by the ascending promotion of renewable energy sources in developed countries. Energy innovation policies have performed to more sustainable development (Balsalobre-Lorente and Shahbaz, 2016). On the other hand, the energy supply breakdowns or energy price shocks have broken down trade balances, leading to inflationary pressures, negatively affecting competitiveness or energy dependency (Bang, 2010; and Ozturk, 2010). In the economic literature, we find extensive awareness that reflects the necessity of increasing environmental sustainability measures, mainly through low-carbon technologies and more efficient energy processes (Álvarez-Herranz *et al.*, 2017). This study provides evidence of the role that

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renewable energy consumption, energy innovation processes, and foreign direct investment (FDI) exert on carbon emissions and how these factors contribute to correct environmental degradation (Wackernagel *et al.*, 1999; and Turner and Hanley, 2011). This research also explores the non-linear linkage between FDI inflows and carbon emission, suggesting that FDI can damage the environment in the first stage of economic development. Hence, as a proxy of the globalization processes, FDI would accelerate structural changes and environmental measures (Abdouli and Hammami, 2017; and Balsalobre-Lorente *et al.*, 2019).

Consequently, this chapter attempts to confirm the rise in pollution intense industries in the G-7 countries by validating the Pollution Haven Hypothesis (PHH) in the first development stage. Even with the well-established economic rationale and theoretical explanations of PHH, some studies refute this hypothesis (Kearsley and Riddel, 2010; Atici, 2012; and Öztürk and Yildirim, 2015). The halo effect implies a negative relationship between FDI inflow and environmental pollution (Atici, 2012). Consequently, the Pollution Halo Hypothesis (PHHH) considers a correction of ecological degradation in the long-run because these countries will entice clean foreign industries, validating the PHHH.

Therefore, this chapter tries to prove that stricter environmental standards in host countries make them less attractive for dirty manufacturing (Chung, 2014; and Neequaye and Oladi, 2015), while lax regulation increases their FDI inflow competitiveness. In other words, highly-polluted countries with less stringent environmental regulations will attract increasing FDI levels (Waldkirch and Gopinath, 2008), since FDI outflows from countries are positively correlated with strict environmental regulations (Aliyu, 2005).

This paper is organized as follows: Sec. 3.2 contains the literature review and some theoretical considerations. Section 3.3 presents the empirical model, the data description, methodology, and econometric results. Section. 3.4 shows the discussion of the results. Finally, Sec. 3.5 contains the main conclusions and the main policy recommendations.

3.2 LITERATURE REVIEW

Since the seminar study proposed by Grossman and Krueger (2019), numerous studies have explored the nexus between economic growth and environmental degradation (Panayotou, 1993; Selden and Song, 1994; Balsalobre-Lorente *et al.*, 2017; Hajko *et al.*, 2018; and Özcan and Öztürk, 2019).

The primary empirical EKC hypothesis proposes a U-inverted relationship (see Fig. 3.1) between economic growth and environmental pollution (Panayotou, 1993; Selden and Song, 1994; Grossman and Krueger, 1995; Dinda, 2004; and Grossman and Krueger, 2019). This empirical evidence suggests that economic systems experiment with a transition from the developing to the developed stage, via scale effect, composition effect, and technical effect. In other words, economic growth will affect environmental quality through these effects (Torras and Boyce, 1998; Balsalobre *et al.*, 2015;

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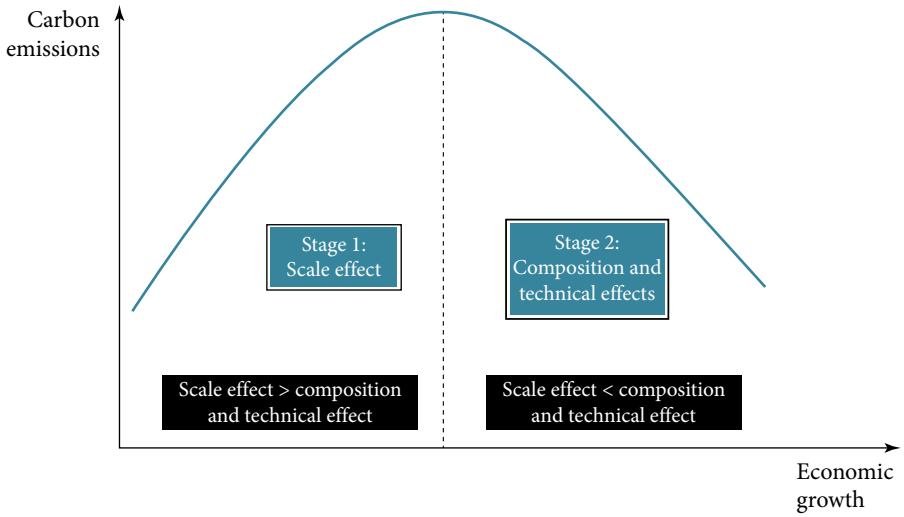
Carbon emissions
Stage 1: Scale effect
Stage 2: Composition and technical effects
Scale effect > composition and technical effect
Scale effect < composition and technical effect
Economic growth

FIG. 3.1
U-inverted EKC's scheme. Prepared by the authors.

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and Grossman and Krueger, 2019). The U-inverted behavior (Fig. 3.1) admits that environmental degradation, in a developing stage of economic growth, increases with ascending income levels, then decreases after a given income threshold is reached. This chapter tries to verify a U-inverted EKC pattern for selected G-7 countries during the years 1992–2016.

Figure 3.1 reflects an enlarged process that expands the income-environmental pollution relationship in the long term (Panayotou, 1993; Grossman and Krueger, 1995; Torras and Boyce, 1998; Balsalobre *et al.*, 2016; Grossman and Krueger, 2019; and Shafik and Bandyopadhyay, 2019). In the early stages of economic development, environmental degradation levels rise until reaching a specific turning point, beyond which economies experience reducing pollution levels. In the first stage of economic development, the *scale effect* discloses that increasing the production function's energy requirements leads to a more extensive use of fossil sources and increased pollution levels (Torras and Boyce, 1998; and Prieur, 2009). The *composition effect* indicates the transition from capital-intensive industrial sectors to service sectors under technology-intensive knowledge economies, which employ cleaner energy procedures. The *technical effect* reflects how high-income economies allocate more resources to energy innovation processes (Andreoni and Levinson, 1998; Markandya *et al.*, 2006; and Balsalobre *et al.*, 2015). High-income economies replace old, dirty, and inefficient technologies with more efficient ones, offering environmental improvements (Copeland and Taylor, 2004; Balsalobre *et al.*, 2016; Balsalobre-Lorente and Alvarez-Herranz, 2016; and Hao *et al.*, 2016), where technological progress

reduces pollution levels (Kumbaroglu, 2003; Vehmas, 2005; Balsalobre-Lorente and Alvarez-Herranz, 2016; and Álvarez-Herranz *et al.*, 2017).

The energy-environment linkage analysis is not new in the energy economics literature (Kraft and Kraft, 1978; Grossman and Krueger, 1995; Sari and Soytas, 2007; Halicioglu, 2009; and Shahbaz *et al.*, 2014). Numerous studies have considered the critical role that energy consumption exerts on economic growth. Although it is well-established in the economic literature that energy consumption is detrimental to the environment, the effects of renewable energy are expected to be different (Bölük and Mert, 2014; and Bölük and Mert, 2015). While numerous studies include both primary energy and fossil fuel consumption to investigate their separate effects on CO_2 emissions (Shafiei and Salim, 2014; and Behera and Dash, 2017), this text explores the impact of renewable energy consumption on carbon emissions for selected G-7 countries. Furthermore, it attempts to demonstrate how the promotion of renewable sources and energy innovation procedures will reduce emissions (Heyes and Kapur, 2011; and Balsalobre *et al.*, 2016).

A significant number of studies have investigated the causal relationship between renewable energy use and the environmental degradation process (Tiwari, 2011; Silva *et al.*, 2012; Sebri and Ben-Salha, 2014; Özbugday and Erbas, 2015; Al-Mulali *et al.*, 2016; Bento and Moutinho, 2016; Bilgili *et al.*, 2016; Dogan and Seker, 2016; Saidi and Mbarek, 2016; and Charfeddine *et al.*, 2018). Silva *et al.* (2012) explored carbon emissions in the USA, Spain, Portugal, and Denmark and concluded that renewable energy contributes to reducing carbon emissions. Bölük and Mert (2014) offered similar results in 16 European Union countries. Irandoust (2016) concluded that renewable energy consumption contributed to reducing carbon emissions in four Nordic countries. Dogan and Seker (2016) showed that expanding renewable energy use decreases carbon emissions in leading renewable energy countries.

Finally, this chapter also tries to confirm a non-linear linkage between FDI and carbon emissions in the G7 countries. Numerous studies have analyzed FDI's effects on environmental quality and economic growth (Anwar and Nguyen, 2010; Azman-Saini *et al.*, 2010; Lau *et al.*, 2014; Neequaye and Oladi, 2015; Shahbaz *et al.*, 2015; Abdouli *et al.*, 2018; and Liu and Lin, 2019). In the first stage of development, the PHH appears as a consequence of the predominant scale effect (Cole and Elliott, 2005; Acharyya, 2009; Al-Mulali, 2012; Kivyiro and Arminen, 2014; Ouyang and Lin, 2015; Shahbaz *et al.*, 2015; Zeren, 2015; Solarin *et al.*, 2017; and Zheng and Sheng, 2017). The pollution haven hypothesis (PHH), proposed by Pethig (1976) and Walter and Ugelow (1979), assumes that the environment is a production factor, which can alter the flow of international capital. Zeng and Zhao (2009) concluded that countries with lax environmental regulations would attract polluting industries. In the same line, other studies showed that a higher level of FDI contributes to promoting manufacturing development, which generates higher energy demand and a higher level of emissions (Abdouli and Hammami, 2017; and Zhu *et al.*, 2017). Shahbaz *et al.* (2015) investigated the non-linear correlation between FDI and environmental degradation for high-, middle-, and low-income countries, concluding that FDI aggravates environmental degradation.

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By contrast, the Pollution Halo Hypothesis (PHHH) argues that the technical effect controls societies and the environment (Al-Mulali and Tang, 2013; Paramati *et al.*, 2016; and Zhang and Zhou, 2016). Liu *et al.* (2017) showed that FDI inflows would reduce carbon emissions due to the use of advanced clean technologies acquired employing FDI. Cole *et al.* (2009) demonstrated that FDI improves environmental standards by transferring clean technology. Hence, FDI would correct environmental pressure due to a multinational firm's transfer of energy-efficient and eco-friendly technologies, cleaner and more efficient (Liang, 2008; Tamazian *et al.*, 2009; Hanna, 2010; Hubler and Keller, 2010; and Liu and Kim, 2018). Kim and Adilov (2012) simultaneously explored the pollution halo and pollution haven hypotheses, which showed that these two are not contradictory. Balsalobre-Lorente *et al.* (2019) validated a non-linear linkage between FDI and the ecological footprint, validating both theories, the PHH and the PHHH, in the same model. During a developing stage, the countries' environmental pollution cost is less than other production costs that countries can gain as a competitive advantage (Copeland and Taylor, 2004). In such a scenario, technology diffusion through FDI inflows aids developing nations to replace old pollution-causing technology (Gallagher, 2004; and Gallagher, 2009).

This chapter evaluates the following hypotheses to assess the connection between economic growth and carbon emissions for selected G-7 countries.

H1: A U-inverted shaped relationship exists between economic growth and *per capita* carbon emissions for selected G-7 countries between 1992 and 2016.
H2: The promotion of renewable sources and energy innovation processes reduces pollution levels.
H3: FDI presents a non-linear connection with carbon emissions.

3.3 EMPIRICAL MODEL AND ECONOMETRIC STRATEGY

To explore our main hypotheses, we present the model as follows. Behind the theoretical scheme outlined by Grossman and Krueger (2019), which links a relationship between environmental pollution and income levels to an inverted U-shape EKC's square scheme [Eqs. (3.1) and (3.2)]

$$\mathrm{CO}_{2_{it}} = \alpha_i + \beta_1 \mathrm{LGDP}_{it} + \beta_2 \mathrm{GDP}^2_{it} + \beta_3 \mathrm{RNWC}_{it} + \beta_4 \mathrm{RNWRDD}_{it} + \beta_5 \mathrm{FDI}_{it} + \varepsilon_{it}, \quad (3.1)$$

$$\mathrm{CO}_{2_{it}} = \alpha_i + \beta_1 \mathrm{LGDP}_{it} + \beta_2 \mathrm{GDP}^2_{it} + \beta_3 \mathrm{RNWC}_{it} + \beta_4 \mathrm{RNWRDD}_{it} + \beta_5 \mathrm{FDI}_{it} + \beta_6 \mathrm{FDI}^2_{it} + \varepsilon_{it}, \quad (3.2)$$

where $\mathrm{CO}_{2_{it}}$ is *per capita* carbon emissions of country i in the year t and GDP_{it} is the income level *per capita*. β coefficients represent the relative importance of exogenous variables, and ε_{it} is the error term, which is generally distributed with zero mean and constant variance. In line with previous literature, gross domestic product (GDP_{it}) *per capita* (current USD) in doing so, the validation of the environmental Kuznets curve (EKC), representing an inverted U-shaped relationship between income and environmental degradation process. The renewable electric consumption (RNWC_{it}) (measured

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Gigajoule *per capita*) and energy innovation process ($RNWRDD_{it}$) (public budget in energy RD&D in current USD) explore the connection between renewable sources and carbon emissions. This text fills the EKC analysis gap through the complementary validation of the non-linear relationship between FDI_{it} (measured in net inflows current USD) and carbon emissions [Eq. (3.2)], which validates both the pollution haven and pollution halo hypothesis for selected G-7 countries. All the variables are extracted from the World Development Indicators Database of the World Bank (2020).

Table 3.1 shows the descriptive statistics and correlation matrix of the selected variables. These statistics are shown as a rough sketch of the candidate variables in the panel of selected countries.

Before running the FMOLS econometric technique, we apply the conventional LLC (Levin *et al.*, 2002), IPS (Im *et al.*, 2003), ADF, and Phillips-Perron PP (Choi, 2001) unit root test to establish that all variables are cointegrated I(1). We then verify a long-run equilibrium relationship between the variables by using Johansen (1991) panel cointegration tests. These traditional panel unit root tests check the stationary properties of selected variables: $LCO_{2\,it}$, $LGDP_{it}$, $LRNWC_{it}$, $LRNWRDD_{it}$,

Table 3.1
Main statistics and correlation matrix (World Bank Database, 2020).

	CO_2	GDP	RNWC	RNWRDD	FDI
Mean	10.932 22	33 510.67	8.351 183	179.543 2	1.819 110
Median	9.449 534	33 846.47	5.625 026	102.541 0	1.422 453
Maximum	20.178 75	55 032.96	22.701 26	2502.962	12.717 56
Minimum	4.573 182	18 389.02	0.608 264	4.104 000	−0.725 184
SD	4.516 649	9674.555	6.529 824	299.184 5	2.052 266
Skewness	0.737 797	0.230 897	1.084 194	4.505 234	2.474 163
Kurtosis	2.164 514	1.905 887	3.032 109	28.422 17	10.765 90
Jarque–Bera	20.726 94	10.166 17	33.900 36	5243.886	611.231 5
Probability	0.000 032	0.006 201	0.000 000	0.000 000	0.000 000
Sum	1891.274	5 797 346.	1444.755	31 060.97	314.706 0
Sum Sq. Dev.	3508.820	1.61×10^{10}	7333.840	15 395 956	724.429 2
	CO_2	GDP	RNWC	RNWRDD	FDI
CO_2	1.000 00				
GDP	0.110 04	1.000 00			
RNWC	0.282 05	0.094 43	1.000 00		
RNWRDD	0.338 66	0.483 50	−0.091 67	1.000 00	
FDI	0.071 15	0.084 90	0.093 54	−0.125 00	1.000 00

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and $LFDI_{it}$. The null hypothesis (non-stationary) in the IPS test can be evaluated using the following equation:

$$\Delta y_{it} = \varphi_{it\beta_{i,t-1}} + \rho * y_{i,t-1} + \sum_{j=1}^{ni} \varphi_{ij} \Delta y_{i,t-j} + \varepsilon_{it}. \tag{3.3}$$

In Eq. (3.3), φ_{it} is the individual deterministic component and ρ is the autoregressive coefficient; ξ_{it} is the error term and n is the lag order. While Levin *et al.* (2002) assume that ρ is constant across the panel, Im *et al.* (2003) extend the LLC test where ρ varies across the panel (IPS test)

$$\Delta y_{it} = \varphi_{it\beta_{i,t-1}} + \rho_i * y_{i,t-1} + \sum_{j=1}^{ni} \varphi_{ij} \Delta y_{i,t-j} + \varepsilon_{it}. \tag{3.4}$$

Individual time series regressions are done for the ADF and PP tests across every cross-section. The *p*-value for each series from their unit root tests is combined instead of averaging individual test statistics (Im *et al.*, 2003). For the LLC, IPS, and Johansen–Fisher unit root tests, the null hypothesis is that each series is non-stationary across individuals (H_0: $\rho_i = 0$), as opposed to the alternative hypothesis, which assumes that at least one individual in the series is stationary (H_1: $\rho_i < 0$). If these tests confirm that the variables are I(1), through the *p*-values, all the series are non-stationary at levels, and we can accept the null hypothesis. We reject the null hypothesis *a priori* at the first difference between them, I(1). The order of integration of the variables is explored using the LLC, IPS, ADF-Fisher, and P-Fisher traditional panel unit root tests (Table 3.2).

In a second step, we use Johansen's Fisher panel cointegration test (Johansen, 1991) to evaluate the selected variables' cointegrating properties to identify a possible long-run relationship between them. This panel cointegration test combines the individual tests and connects tests from individual cross-sections. Π_i is the *p*-value from an individual cointegration test for cross-section *i*. Under the null hypothesis for the panel

$$-2\sum_{i=1}^{N} \log(\Pi_i) \rightarrow \chi^2 2N, \tag{3.5}$$

where χ^2 values (MacKinnon *et al.*, 1999) and *p*-values are reported for Johansen's cointegration trace and the maximum eigenvalue tests. The results of the Johansen–Fisher panel cointegration test are recorded in Table 3.3.

Once we have determined a long-run relationship between the variables, the FMOLS estimation methodology (Phillips and Hansen, 1990) offers an adjustment for serial correlation and endogeneity due to cointegrating relationships where

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Table 3.2
Unit root analysis.

	(A) Null: unit root (assumes common unit root process)		(B) Null: unit root (assumes individual unit root process)					
	Levin, Lin, and Chu t		Im, Pesaran, and Shin W-stat		A.D.F.—Fisher chi-square		PP—Fisher chi-square	
	t-statistic	p-value	t-statistic	p-value	t-statistic	p-value	t-statistic	p-value
CO_2	2.987 70	(0.998 6)	3.348 93	(0.999 6)	7.409 91	(0.917 8)	7.235 65	(0.925 2)
GDP	0.254 37	(0.600 4)	1.881 63	(0.970 1)	7.624 64	(0.908 0)	6.005 32	(0.966 4)
RNWC	6.458 44	(1.000 0)	6.692 73	(1.000 0)	2.456 47	(0.999 7)	3.744 77	(0.996 8)
RNWRDD	2.386 68	(0.991 5)	2.568 91	(0.994 9)	4.819 39	(0.988 2)	8.711 11	(0.849 1)
FDI	−1.919 26*	(0.027 5)	−2.735 90*	(0.003 1)	29.480 7*	(0.009 0)	35.607 3*	(0.001 2)
ΔCO_2	−2.831 63*	(0.002 3)	−4.940 89*	(0.000 0)	51.252 6*	(0.000 0)	125.580*	(0.000 0)
ΔGDP	−6.502 46*	(0.000 0)	−5.855 68*	(0.000 0)	59.690 5*	(0.000 0)	61.958 9*	(0.000 0)
ΔRNWC	−2.927 23*	(0.001 7)	−4.258 14*	(0.000 0)	54.014 9*	(0.000 0)	97.990 5*	(0.000 0)
ΔRNWRDD	−5.559 55*	(0.000 0)	−6.144 12*	(0.000 0)	63.987 7*	(0.000 0)	143.973*	(0.000 0)
ΔFDI	−5.247 80*	(0.000 0)	−6.768 49*	(0.000 0)	69.662 8*	(0.000 0)	151.096*	(0.000 0)

Note: *, **, and *** significance at 1%, 5%, and 10%.

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Table 3.3
Johansen–Fisher panel cointegration test.

Unrestricted cointegration rank test (trace and maximum eigenvalue)				
Hypothesized No. of CE(s)	Fisher Stat.[a] (from trace test)	Prob.	Fisher Stat.[a] (from max-eigen test)	Prob.
None	135.0*	(0.000 0)	92.68*	(0.000 0)
At most 1	58.31*	(0.000 0)	44.89*	(0.000 0)
At most 2	25.72*	(0.028 1)	14.99	(0.379 0)
At most 3	21.85*	(0.081 8)	15.01	(0.377 8)
At most 4	25.22*	(0.032 4)	25.22*	(0.032 4)

[a]Probabilities are computed using asymptotic Chi-square distribution. *, **, and *** significance at 1%, 5%, and 10%.

$$Y_{i,t} = \alpha_i + \beta_i X_{i,t} + \varepsilon_{i,t} \quad \forall_t = 1,\ldots,T, i = 1,\ldots,N, \tag{3.6}$$

$Y_{i,t}$ and $X_{i,t}$ are cointegrated with slopes β_i.

The FMOLS econometric technique is intended to address endogeneity, simultaneity bias, and non-stationary regressors that are the primary concerns in panel analysis (Christopoulos and Tsionas, 2004). Spurious regression, when the series is non-stationary, results from the use of normal OLS techniques. If the cointegration relation occurs, then a long-run relationship exists between the variables. FMOLS technique is used because, in cases where the variables are I(1), OLS estimation yields biased estimators. The FMOLS estimation is a non-parametric approach that produces optimal cointegrating regression results (Phillips and Hansen, 1990). It is designed to make adjustments for serial correlation and endogeneity due to the presence of cointegrating relationships.

3.4 EMPIRICAL RESULTS

In the first step of our econometric strategy, we check the data series's stationarity properties by using the selected first generation of unit root tests (Table 3.2).

The LLC, IPS, ADF, and PP-Fisher tests (Table 3.2) confirm that the series is non-stationary, verifying that all selected variables are integrated to order one, I(1).

In a second step, the Johansen–Fisher panel cointegration test checks the cointegrating relationship among the selected variables in the long-run (Table 3.3). Table 3.3 explores the existence of a long-run equilibrium between the variables $LCO_{2_{it}}$, $LGDP_{it}$, $LRNWC_{it}$, $LRNWRDD_{it}$, and $LFDI_{it}$.

The Johansen–Fisher panel cointegration test indicates that the present variables are cointegrated at a 1% significance level, so we confirm that these variables are associated for the long-run. Once we have determined, through the proposed cointegration tests, the validation of a long-run connection between the variables, we can apply the FMOLS technique (Phillips and Hansen, 1990). This econometric methodology is suitable for serial correlation and endogeneity, which generates unbiased and normally distributed coefficient outcomes. Table 3.4 contains the FMOLS econometric results based on Eqs. (3.1) and (3.2).

3.5 DISCUSSION OF RESULTS

The empirical results (Table 3.4) validate the EKC hypothesis for the G-7 countries by using the FMOLS econometric panel of aggregated countries. We confirm that in the early stages of economic growth, CO_2 emissions increase ($\beta_1 > 0$) along with the rise in per capita income (GDP). However, at the later stages of development, CO_2 emissions decrease ($\beta_2 < 0$) when the composition and technical effects

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Table 3.4

FMOLS econometric results.

Dependent variable: LCO_2 **Method: Panel fully modified least squares (FMOLS)** **Sample (adjusted): 1992–2016**		
Variable	**Equation (3.1) Coefficient**	**Equation (3.2) Coefficient**
GDP	0.000 170*	0.000 165*
	[11.063 49]	[11.921 59]
	(0.000 0)	(0.000 0)
GDP^2	-2.67×10^{-9}*	-2.65×10^{-9}*
	[−12.187 40]	[−13.45566]
	(0.000 0)	(0.000 0)
RNWRDD	−0.000 618*	−0.000 585*
	[−8.155 566]	[−9.715 899]
	(0.000 0)	(0.000 0)
RNWC	−0.176 929*	−0.177 042*
	[−19.438 24]	[−20.888 26]
	(0.000 0)	(0.000 0)
FDI	0.046 757*	0.156 659*
	[5.084 870]	[6.583 724]
	(0.000 0)	(0.000 0)
FDI^2	…	−0.011 165*
	…	[−4.967 431]
	…	(0.000 0)
R^2	0.989 160	0.989 374
Adjusted R^2	0.988 386	0.988 540
SE of regression	0.486 889	0.483 639
Long-run variance	0.050 832	0.045 532
Mean dependent var	10.939 31	10.939 31
SD dependent var	4.517 879	4.517 879
Sum squared resid	36.507 37	35.787 71

Note: *, **, and *** significance at 1%, 5%, and 10%.

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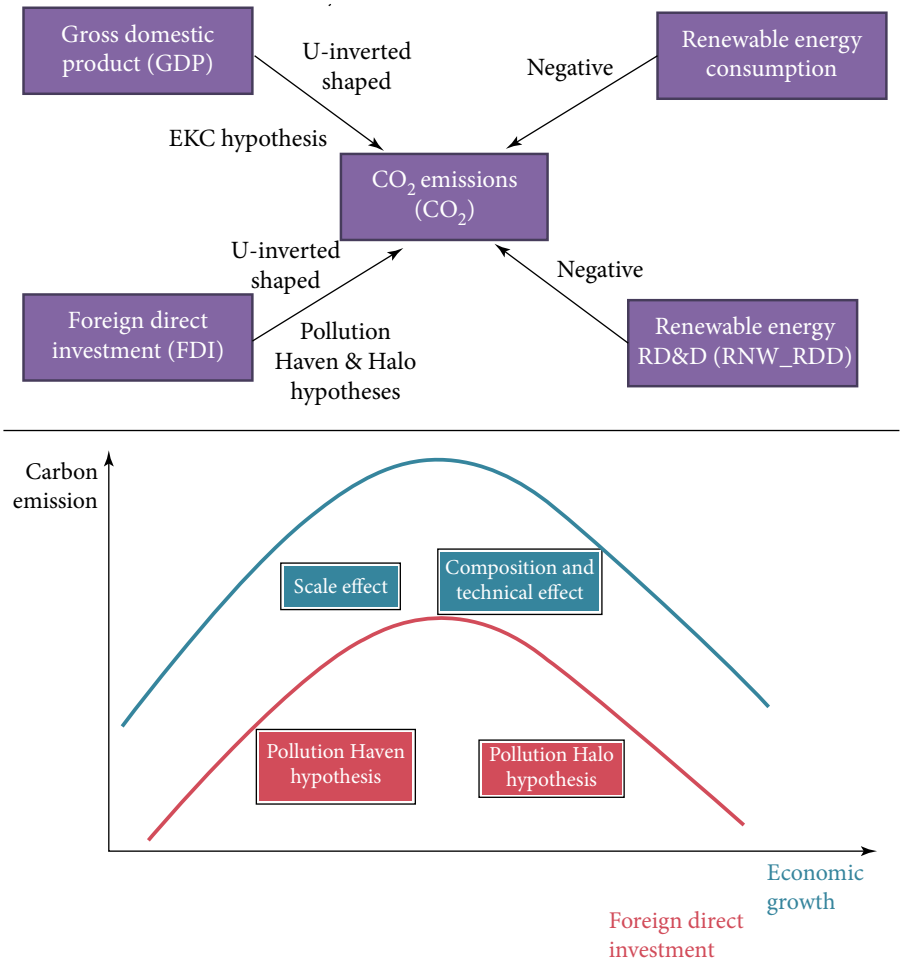

FIG. 3.2
FMOLS econometric scheme.

overcome the scale effect (Balsalobre *et al.*, 2016). Therefore, we evidence of a U-inverted (Fig. 3.2) linkage between economic growth and CO_2 emissions for the selected G-7countries (Selden and Song, 1994; Grossman and Krueger, 1995; Torras and Boyce, 1998; Balsalobre *et al.*, 2016; Balsalobre-Lorente and Alvarez-Herranz, 2016; Álvarez-Herranz *et al.*, 2017; Grossman and Krueger, 2019; and Shafik and Bandyopadhyay, 2019).

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The coefficients $\beta_3 < 0$ and $\beta_4 < 0$ reinforce renewable sources' positive effect to control pollution. Consequently, reducing the share of fossil sources in the energy mix in G-7 countries would reduce CO_2 emissions. This evidence connects with empirical literature that affirms that the energy consumption structure is a main driving force in the environmental correction process (Wu *et al.*, 2009; and Tsao *et al.*, 2012). Wang (2005) showed that environmental correction is due to energy innovations and reductions in fossil sources' share. In the same line, He *et al.* (2018) showed that technical advances and changes in economic systems' structure alter the connection between energy use and environmental quality. To consolidate the positive impact of renewable energy on the environmental correction process, G-7 governments need to promote energy efficiency innovation and clean energy sources (Balsalobre-Lorente and Alvarez-Herranz, 2016; and Álvarez-Herranz *et al.*, 2017).

Finally, the non-linear $\beta_5 > 0$ and $\beta_6 < 0$ connection between FDI and CO_2 emissions (Fig. 3.2) in the G-7 countries (Bakirtas and Cetin, 2017; Balsalobre-Lorente *et al.*, 2019; and Shahbaz *et al.*, 2019). The evidence reveals a transition to clean foreign business, environmental degradation. This evidence suggests a combination of Pollution Haven (PHH) and Halo Hypotheses (PHHH), where ascending globalization is more environmentally friendly. The econometric results reveal that FDI accelerates the traditional business transition to high-tech industries (Adedoyin *et al.*, 2020). These results validate that the globalization process contributes to improving efficiency and the technical progress in host countries in the G-7 countries (Torras and Boyce, 1998; List and Co, 2000; Tisdell, 2001; Wang, 2005; Tamazian *et al.*, 2009; and He *et al.*, 2018).

3.6 FINAL CONCLUSIONS

This chapter analyzes the trajectory of income, renewable energy, innovation, and FDI on carbon emissions in the G-7 countries between 1992 and 2016. As the central part of this research, we explore the non-linear relationship between FDI and carbon emissions in the G-7 countries. From FMOLS econometric methodology, we find a U-inverted connection between economic growth, FDI, and carbon emissions. The empirical results verify the EKC while also confirming both the PHH and PHHH for the G-7 countries. The EKC hypothesis's validation implies a transition from a developing to a developed economic system due to ascending income levels and a shift from the scale to technical effect.

On the other hand, the results support the pollution haven and halo hypotheses in the G-7 countries, implying a transition from polluting industries to clean and high-tech industries in host countries. These results support the theory that FDI inflows increase carbon emissions in the early stages. Contrariwise, once the G-7 countries have reached a specific turning point, rising FDI inflows would reduce the carbon emission due to cleaner industries and more efficient energy processes in these countries. The minoration of the pernicious impact of FDI on the environment in the early stages of economic development is a consequence of the attraction of clean industries and the promotion of energy innovation measures (Balsalobre-Lorente *et al.*, 2019; and Shahbaz *et al.*, 2019). These efforts are justified by the transition from dirty economic systems to more effective and cleaner economic systems.

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Otherwise, the most evident increase of environmental degradation that appears in the early stages of economic growth is corrected at the later stages of the growth process by renewable energy consumption and renewable energy innovation. Renewable energy consumption and energy innovation processes shed some exciting results regarding a more sustainable and energy-efficient economic system. This chapter confirms the low-carbon development hypothesis, which suggests that the economic cycle helps to reduce the energy sector's inefficiency. It is necessary to adopt measures to modify the energy mix pattern. The empirical results admit environmental policy recommendations related to promoting renewable energy use and energy innovation processes.

This study contributes to advancing the empirical literature evidence that jointly explores the PHH and PHHH under an EKC scheme based on the stated results. As we outlined above, rising FDI will generate improvements and enhance more efficient manufacturing uses and cleaner technologies. This evidence results useful for policymakers in adopting measures that accelerate the transition from a developing stage, attracting clean and high-tech industries in the G-7 countries. These environmentally riendly regulations would impulse sustainable growth and the reduction in the share of fossil sources. This chapter outlines some alternatives that encompass a wide range of non-regulatory and regulatory approaches that the state may wish to consider if it determines that further actions are needed to protect environmental quality in the G-7 countries.

Lastly, this chapter offers some relevant policy implications for selected G-7 countries. First, policymakers should consider promoting renewable energy in both the government and private sectors of these countries. In this sense, the governments should promote the renewable energy and energy innovation processes (e.g., electric cars, promotion of hydro, solar, or wind energies), where the private sector may adopt measures in strategic sectors like tourism, energy industry, or tertiary sector. The attraction of clean FDI would provide investments in R&D, environmentally-friendly technologies, and the ascending of clean business in host countries. In this sense, it would be necessary to increase efforts to improve environmental policies and institutions instead of limiting FDI and globalization activities that reduce environmental quality. Future studies should focus on the analysis of additional explanatory variables, like tourism or financial development. Furthermore, the crisis of COVID-19 has implied an impact on these economic systems that would be necessary to explore in future studies.

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CHAPTER

4 RENEWABLE ENERGY AND NANOTECHNOLOGY

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4.1 INTRODUCTION

The world crisis is attributed to the nonavailability of traditional fuel as a result of the increased consumption of the mentioned fuel. It is known that the current consumption of fuel is 105 times larger than its creation, so the quantity will be ended as expected before 2050 (Demirbas, 2009), in addition to dramatically increasing energy demand to 30–46 TW before the end of the current century (Ahmad and Zhang, 2020). Coal, oil, and gas are the traditional sources of energy. These are nonrenewable energy sources, so when burnt, they will be gone forever. They meet 90% of demand, but they are costly to the environment, as proved by the increasing CO_2 concentrations to 370 ppm over a century ago, and it can also be increased to 550 ppm in the coming years (Lund, 2007). This is a critical point to a serious shift to renewable energy due to decreasing traditional fuel as a result of huge consumption. Renewable energy can be used instead of conventional fossil fuels and nuclear energy. Nowadays, there is huge interest in this subject since it is expected to provide 50% of the world's primary energy by 2040. Moreover, renewable energy can play a crucial role in reducing gas emissions in the environment by about 70% by 2050. On the other side, a new scientific field called nanotechnology has gained considerable attention in recent years due to many engineering and technological applications. Therefore, this reduction in size leads to reducing required energy. Also, there are many benefits that can be observed from the design of nanotechnology-based products for renewable energy, which are as follows:

1. Increased efficiency of lighting and heating.
2. Increased electrical storage capacity.
3. A decrease in the amount of pollution from the energy use.

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The nanotechnological features of the economy and society have encouraged the companies and government for investment (Shapira and Youtie, 2011). In the microworld, these could emerge in a completely different way than others. The fantastic engineering of nanotechnology gives freedom for building nanoelectronics exceeding the current technologies but displaying novel characteristics, attractive techniques, cost-effectiveness, and environmentally friendly features (Aono *et al.*, 2012). It is confirmed that nanotechnology has distinguished and unique properties for solving contemporary problems with current technologies that can change the processes, techniques, and design of our life, institutions, establishments, and requirements (Whitesides, 2005).

The sustainability, nanotechnology, energy storage and conversion, and environment have been investigated by Brinker and Ginger (2011) to explain that the principal reduction of energy is attributed to thermoelectricity waste heat recovery devices. In addition, a comprehensive study of energy strategies for lowering greenhouse gas emissions and membrane-based desalination has been reviewed by Subramani *et al.* (2011). They have reviewed the high efficiency pumping, utilization of energy efficient designs, innovative technologies, energy recovery devices, wind, solar, and geothermal energy resources, and nanotube, nanocomposite, and biomimetic advanced membrane materials. Also, they have deduced that the desalination process could be lessened via utilizing progressed membranes applicable to innovative nanotechnologies. Other types of renewable energies like solar, hydrogen, and biotechnology-based nanotechnology have been reviewed by Guo (2012) including patents for profiting from future environmentally friendly energy. On the other hand, Grebler and Nentwich (2012) have presented a work about the relationship between the nanomaterials and the environment. Yu and Xie (2012) have studied the nanofluids such as preparation methods, evaluation methods for the nanofluids stability, and mechanisms and ways to improve the stability of the nanofluids. They have displayed a wide range of nanofluid applications in different fields such as biomedical, mechanical, and energetic fields. In addition, the benefit of sustained and efficient information and communication technology (ICT) in nanotechnology is presented by Markovic *et al.* (2012). Nanotechnology could present benefited applications in logic elements, smarter sensors, memory storage devices, computer chips, quantum computing, and optoelectronics. Tan *et al.* (2012) have reviewed the applications and advantages of carbon nanotubes in energy conversion and storage such as in solar cells, fuel cells, hydrogen storage, lithium ion batteries, electrochemical super capacitors, and green nanocomposite design. The nanomaterial-based energy applications are investigated by Daryoush and Darvish (2013). The polymer-based nanocomposite materials were displayed during the 1970s utilizing the sol–gel method for dispersing mineral nanoparticles into a polymer.

This chapter intends to present different and important applications of renewable energy-based nanotechnology with a reference to theoretical research to predict and verify specific models for nanotechnology in renewable energy. It is aimed to verify our model for calculating the diameter dependence on the QDs potential for different dot diameters for semiconductors using the full potential linearized augmented plane wave (FP-LAPW) to investigate the optical properties utilizing specific models for the mentioned materials. The rest of this chapter is organized as follows: Sec. 4.2

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describes the nanotechnological features. Section 4.3 presents the nanotechnology investment in renewable energy. Section 4.4 describes nanotechnological applications for renewable energy. Finally, the conclusions are summarized in Sec. 4.5.

4.2 NANOTECHNOLOGICAL FEATURES

New features of nanotechnology such as materials, physics, and semiconductors are discussed. Those features illustrate many characteristics and properties of the mentioned areas, although they are overlapped in specific points. The behavior of a material at the nanoscale differs from that of a bulk material because the nanoscale has a large surface area and increased reactivity, allowing the quantum effect to dominate.

4.2.1 Materials

The material's behavior in the nanoscale is different from the bulk one because the nanoscale has the feature of a wide surface area and increased reactivity, allowing the quantum effect to dominate.

1. 3D structure: the materials can be categorized by the compound class and structure dimensionalities. Successful commercialization has been gained by 1D dimensions (Bonnell, 2003). The new products of 3D (particles), 2D (monolayers), 1D (tubes and wires), and 0D (dots) for practical applications.
2. The correlation between size and surface to volume ratio is inverse. The decreasing change of material dimensions from macro- to nano-size leads to total changes in chemical, optical, mechanical, and physical properties.
3. Quantum effect: quantum mechanics is a developed field of physics dealing with physical features on nanoscale toward direct action of the Planck constant. Several features have pronounced as materials size decreases. Anyway, the quantum effect is observed when the material size reaches nanoscale for less than 100 nm as called the quantum realm. In addition, different physical (electrical, mechanical, optical, thermal, and other) properties are changed compared to macro-size systems. Quantum confinement dominates at the nanoscale for all optical and electrical properties (Loss, 2009). The interest is focusing on quantum dots (QDs) that are semiconductor material nanoparticles, which could be "tuned" to absorb or emit specific light colors for use in fluorescent biological labels or solar cells. The quantum confinement localizes electrons in quantum dots by occupying atomic states with discrete energy levels. So, the quantum dots escorting with confined electrons are known as artificial atoms (Maksym and Chakraborty, 1990).

4.2.2 Physical

The physical properties of nanoparticles are often different from the same properties in macro-size. Those properties are depending on their size, inner structure, shape, and surface characteristics (Kongsat *et al.*, 2021).

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1. Self-assembly is a feature where their system components interact with each other to create a big functional unit for assembling themselves spontaneously. This type of spontaneous system could occurr within direct/indirect interaction outside of their environment. The research of nanomaterials becomes more important due to the advancement of technologies worldwide. It is crucial to assemble nanoparticles within one configuration for developing nanoelectronics, which are small in size but contain huge information.
2. The gradients of the magnetic field are utilized to manipulate magnetic nanoparticles. Those nanoparticles are consisting of magnetic elements such as cobalt, iron, nickel, and their alloys. The physical studies of magnetic nanoparticles are largely depending on the chemical structure and synthesis method.
3. The applied electric field is applied to any type of electrical insulator known as dielectric to be polarized. The placing of the dielectric under electric field promotes to shift a little from average equilibrium position to create dielectric polarization case, in contrary to a direct flow of electric charges within the conductor material.

4.2.3 Semiconductors

The electronics are constating of semiconductors that are existing in two different types: compound materials and elemental materials (Neamen and Pevzner, 2003).

1. The nanotube is a tube-like structure on nanoscale. The semiconductors are recommended for nanotubes for three terminal nanodevices. To bridge two metal electrodes, the nanotube is utilized and positioned that is drain and source of field-effect transistors (FETs). The wafer of silicon is utilized as a gate. Those nanodevices are behaving as unipolar p-type FETs with off/on current switching ratios of $\sim 10^5$.
2. When the length of nanotubes is larger than 1 μm, they are called nanofibers or nanowires. One of the nanotechnological applications and features is nanowires that are deserved for study and research. They are synthesized by a research team of physicists or chemists to produce semiconductors and metallic nanowires (Korgel and Fitzmaurice, 1998).
3. The research and study of quantum dots (QDs) have arisen a long time ago through low dimensional electron gases, heterostructures, and quantum wells semiconductors (Bonnell, 2003). The challenges are presented with quantum dots (QDs) within tunable optical emission frequencies, which are attributed to quantum size confinement.

4.3 NANOTECHNOLOGY INVESTMENT IN RENEWABLE ENERGY

There are three general methods of manufacturing nanomaterials by suspending nanoparticles into base fluids. These methods can be classified as follows (Gupta *et al.*, 2012):

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1. Addition of acid or base to change the pH value of a suspension.
2. Adding surface active agents and/or dispersants to disperse particles into the fluid.
3. Using ultrasonic vibration.

In general, materials can have different properties at the nanoscale. Those properties are better conductivity, reflecting light, very light, more stable, and high stronger, in addition to present properties of the chemically active and magnetic features. These features or properties are attributed to a nanoscale of less than 100 nm, the known rules of chemistry and physics are not necessarily applied. So, it is normal to receive wonder signs of researching or applying those properties. The nanomaterials are stronger and conductive electrically and their reaction increases dramatically. The new outputs of studying nanomaterials open the horizon to further research for better life quality and a prosperous society. Further research studies on nanomaterials are detailed and reviewed by Suh *et al.* (2009) and Savolainen *et al.* (2010). The devices of energy storage like super-capacitors and batteries can significantly modify them by applying nanotechnology. Nanotechnology has the ability to engineer the relevant materials and components of lithium-ion batteries for heat resistant, high-performance electrodes and flexibility. The nanoporous materials such as zeolites are one of the nanotechnological features to improve the storage of thermal energy for saving the heat in both industrial residential zones. Otherside, the nanomaterials can be categorized on their methods or techniques as Elcock referred (Elcock, 2007). He has mentioned the difficulties and something costly ways to synthesize nanoparticles, although they have the potential to affect energy use and the development of electronics, transportation, manufacturing, and others. While nanotechnology-based renewable energy techniques have been developed and explained by Mao and Chen (2007). Those techniques are (1) employing solar cells to convert the sunshine into electric current, (2) splitting water into its elements to convert solar energy into hydrogen fuel, (3) utilizing solid-state forms to store hydrogen, and (4) employing fuel cells for generating electricity via hydrogen. Serrano *et al.* (2009) have reviewed some advances in nanotechnology for sustainable energy production, storage, and use. They have displayed many advantages of nanotechnology-based sustainable energy:

1. Increasing efficiency of photovoltaics (PVs), in parallel with reducing costs of manufactured electrical productions at an unprecedented rate.
2. Nanomaterials lead to improve the hydrogen transformation, storage, and production into electrical fuel cells. This happens by increasing the capacity of hydrogen adsorption leading to fuel cells being cheaper and more efficient.

4.4 NANOTECHNOLOGICAL APPLICATIONS FOR RENEWABLE ENERGY

4.4.1 Si element

Due to the nearest neighbors being bound by overlapping hybridized orbitals and density is low that are attributed to covalent semiconductors sp^3 hybrids with tetrahedral direction (Liu *et al.*, 2019), the

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Table 4.1
Different dot diameters (in nm) dependent on calculated principal E_g for Si (in eV) in comparison with other experimental and theoretical data (Al-Douri *et al.*, 2011).

Dot diameter	E_g (Γ→Γ)	E_g (Γ→X)	E_g (Γ→L)
54.3	2.742	1.436; 1.11[a,b]	2.028
54	2.747	1.396	2.094
53.6	2.751	1.352	2.164
53.3	2.757	1.272	2.279
53	2.752	1.345	2.174
52.7	2.759	1.233	2.332

[a]Kohn and Sham (1965) Expt.
[b]Perdew *et al.* (1996).

covalent semiconductors have fourfold coordinates. Therefore, the dot diameter has been used to tune the bandgap (E_g). The EVGGA is used to calculate the values of indirect (Γ→L) and (Γ→X), and direct (Γ→Γ) bandgap to investigate Si element at different measurements of diameters as displayed in Table 4.1 including experimental (Zhang *et al.*, 2020) and other theoretical data (Humphreys *et al.*, 1978). It is observed that the calculated values of $E_{g\Gamma\to X}$ are overestimated in comparison with other data, attributing to utilizing EVGGA approximation. The Si element is classified into a narrow E_g semiconductor due to the small bandgap. The dot diameter variations give a special interest to research as the Si energy gap is in the infrared zone and its importance for detection and light generation. Table 4.1 illustrates the decrease of E_g at point X. Also, Fig. 4.1 shows the E_g variation as a function of dot diameter, it is noticed the Γ→X increases and Γ→L and Γ→Γ decrease to confirm Si is an indirect gap semiconductor.

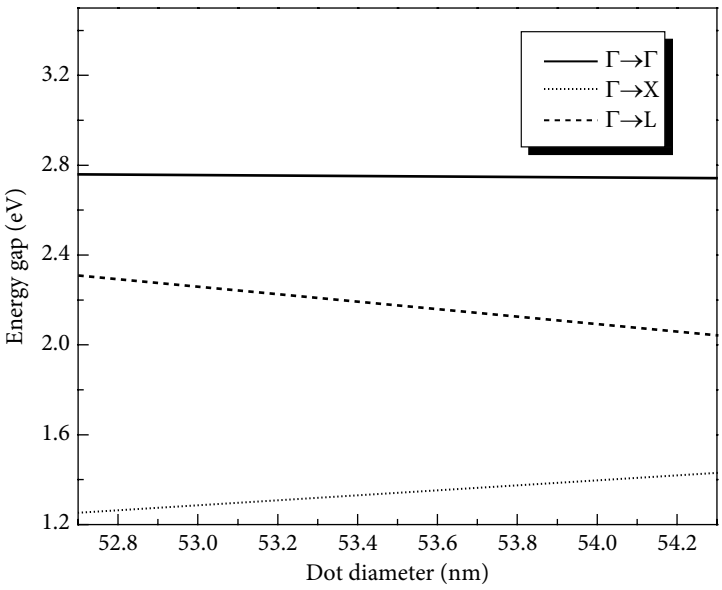

FIG. 4.1
Different dot diameters dependent calculated indirect (Γ→L) and (Γ→X), and direct (Γ→Γ) Eg (Al-Douri *et al.*, 2011).

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Table 4.2
Different dot diameters (in nm) dependent on calculated QDs potential for Si (in eV) in comparison with others (Al-Douri *et al.*, 2011).

Dot diameter	P_{QD} Cal.	P_{QD} (Udipi *et al.*, 1996)
54.3	1.051	≤1
54	1.021	
53.6	0.989	
53.3	0.931	
53	0.984	
52.7	0.902	

The FP-LAPW has been employed to calculate the E_g between conduction band minimum (CBM) at X and valence band maximum (VBM) at Γ. Using our model (Al-Douri, 2009), the quantum dot potential has been evaluated, according to the formula

$$P_{QD} = \frac{b}{a} \cdot E_{g\Gamma X} \cdot 10^{-3} \cdot \lambda, \tag{4.1}$$

where the constant refers to $\frac{b}{a}$ (in eV^{-1}) [see Table 4 in Al-Douri, 2009)] and the appropriate parameter refers to λ for II–VI ($\lambda = 2$), III–V ($\lambda = 4$) and group-IV ($\lambda = 6$) semiconductors (in V).

When the diameter decreases, the strong covalent bonding sp^3 is varied. So, the resulted difference in quantum dot potential is a result of different dot diameters. Hence, Table 4.2 presents dot diameter dependent calculated quantum dot potential. The separation between increasing and decreasing quantum dot potential is called a critical dot diameter value. The correlation between dot diameter and transition pressure (P_t) is necessary to be calculated from the molar free energies difference. The ΔG_t refers to Gibbs free-energy difference between different tetrahedral compounds, which is given by $P_t \Delta V/V_t$ (in kJ/mol). So, the energies are bigger for smaller bond lengths. The correlation between principal energy gaps and dot diameter is inverse as observed in Table 4.1 to confirm that the energy band positions are changed at the principal points of the Brillouin zone.

The correlation between QDs potential and dot diameter is direct until reaching the critical value as verified by random behavior (Table 4.2) and fixed by Fig. 4.2. Consequently, there is an appeared fluctuation of QDs potential. It is noticed an agreement of calculated QDs potential values and others (Balzaretti and da Jornada, 1996). So, reaching the sudden difference of QDs potential value is a control reference of tunneling electron across the QDs.

The refractive index n is a very important physical parameter related to microscopic atomic interactions. From a theoretical viewpoint, there are basically two different approaches of viewing this subject: the refractive index will be related to the density and the local polarizability of these entities (Al-Douri *et al.*, 2008). Consequently, many attempts have been made in order to relate the refractive index and the energy gap E_g through simple relationships (Herve and Vandamme, 1994). However, these relations of n are independent of temperature and incident photon energy. Here, the various relations between n and E_g will be reviewed. Ravindra *et al.* (1979) had been presented a linear form of n as a function of E_g,

$$n = \alpha + \beta E_g, \tag{4.2}$$

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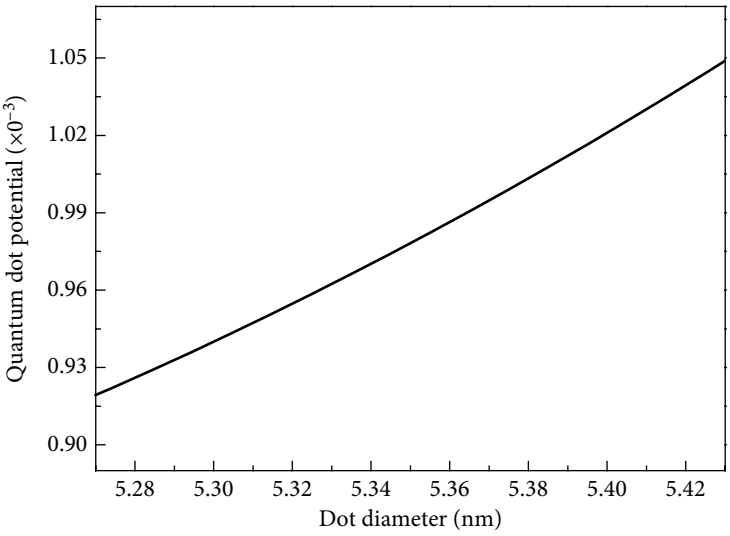

FIG. 4.2
Dot diameter dependence of the quantum dot potential for Si (Al-Douri *et al.*, 2011).

where $\alpha = 4.048$ and $\beta = -0.62$ eV^{-1}. Light refraction and dispersion will be inspired. Herve and Vandamme (1995) proposed an empirical relation as follows:

$$n = \sqrt{1 + \left(\frac{A}{E_g + B}\right)^2}, \tag{4.3}$$

where $A = 13.6$ eV and $B = 3.4$ eV. For group-IV semiconductors, Ghosh *et al.* (1984) have published an empirical relationship based on the band structure and quantum dielectric considerations of Penn (1962) and Van Vechten (1969),

$$n^2 - 1 = \frac{A}{(E_g + B)^2}, \tag{4.4}$$

where the average E_g is $(E_g + B)$, $B = 0.225E_g + 2.25$ and $A = 8.2E_g + 134r$. So, utilizing dot diameters dependent variations of n have been computed. It is verified by the calculated refractive index dependent optical dielectric constant ε_∞. It is noticed $\varepsilon_\infty = n^2$ (Samara, 1983). Therefore, the Ghosh *et al.* model (Ghosh *et al.*, 1984) to calculate the n is agreed well with experimental data because the reflectivity concept is important for enhancing the conversion of light in solar cells. Also, the dot diameter linear dependent of Si characteristics is noticed, where there is shifting to blue–green zone for smaller diameters, that is meaning higher absorption and lower reflection that is attributing to increased efficiency of solar cells.

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4.4.2 Cd alloys

As mentioned earlier, the covalent semiconductors of tetrahedral shape are fourfold coordinates and have low structure density, bounded nearest neighbors' atoms of sp^3 hybrids with a possibility of tuning E_g in terms of dot diameters. Table 4.3 presents the calculated E_g values of indirect ($\Gamma \rightarrow L$) and ($\Gamma \rightarrow X$),

Table 4.3

The calculated principal energy gaps for $CdS_{0.75}Te_{0.25}$, $CdS_{0.5}Te_{0.5}$, and $CdS_{0.25}Te_{0.75}$ alloys (in eV) at different QD diameters (in nm) compared to other experimental data and theoretical results (Al-Douri *et al.*, 2015a).

QDs diameter	E_g ($\Gamma \rightarrow \Gamma$)	E_g ($\Gamma \rightarrow X$)	E_g ($\Gamma \rightarrow L$)
CdS	2.359, 2.42[a] 2.361[b]	4.626	3.432
CdTe	1.368, 1.8[c] 1.8[d]	3.241	2.288
$CdS_{0.75}Te_{0.25}$			
61	0.943	0.943	2.484
60	1.067	0.949	2.609
59	1.187	0.955	2.731
58.5	1.306	0.960	2.850
58	1.422	0.964	2.967
57.5	1.535	0.968	3.082
$CdS_{0.5}Te_{0.5}$			
63	0.730	2.737	2.583
61.5	0.853	2.743	2.707
60.5	0.974	2.748	2.829
60	1.092	2.753	2.949
59	1.208	2.758	3.066
58	1.321	2.761	3.180
$CdS_{0.25}Te_{0.75}$			
65	0.650	0.650	1.538
63.5	0.774	0.657	1.663
62.5	0.895	0.662	1.785
61.5	1.013	0.667	1.940
61	1.129	0.670	2.021
60	1.242	0.675	2.136

[a]Al-Douri *et al.* (2015a) Expt.
[b]Feng *et al.* (1993) Theor.
[c]Tsidilkovski (1982) Expt.
[d]Al-Douri *et al.* (2001) Theor.

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and direct (Γ→Γ) E_g via EVGGA to investigate dot diameter dependent $CdS_{1-x}Te_x$ alloys compared to experimental (Tsidilkovski, 1982; and Al-Douri *et al.*, 2015a) and theoretical results (Zemel *et al.*, 1965; and Al-Douri *et al.*, 2015b). The mentioned values of (Γ→Γ) E_g are underestimated in comparison to the experimental ones due to specific considerations of employing EVGGA approximation. So, $CdS_{1-x}Te_x$ alloys have been categorized as direct E_g semiconductors. The dot diameter dependent QDs potential is important research and recommended for infrared light detection and generation applications. Hence, Table 4.3 displays the inverse correlation of E_g and dot diameters as verified by Fig. 4.3.

The FP-LAPW is utilized to compute the E_g between conduction band minimum (CBM) at the X and valence band maximum (VBM) at Γ. Our model (Al-Douri, 2009) has proved that QDs have evaluated

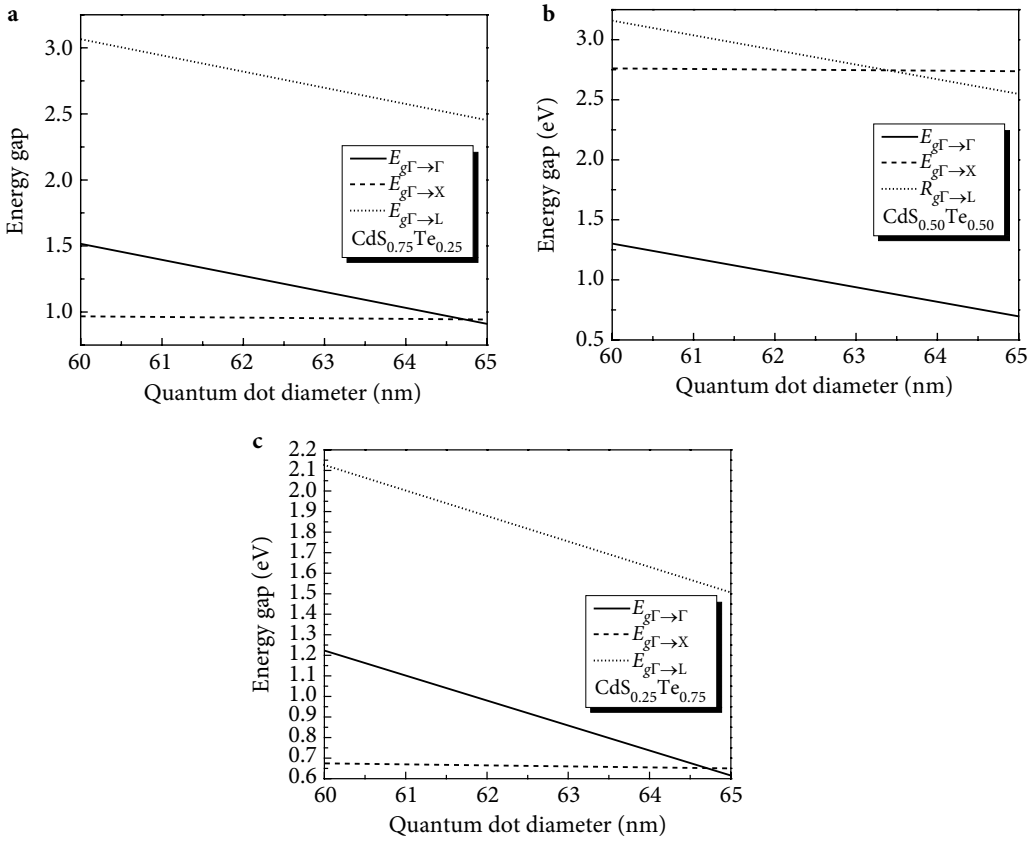

FIG. 4.3
Calculated energy bandgaps direct (Γ→Γ), and indirect (Γ→X) and (Γ→L) for (a) $CdS_{0.75}Te_{0.25}$, (b) $CdS_{0.5}Te_{0.5}$, and (c) $CdS_{0.25}Te_{0.75}$ alloys as a function of QDs diameter (Al-Douri *et al.*, 2015a).

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Table 4.4
The calculated quantum dot potential for $CdS_{0.75}Te_{0.25}$, $CdS_{0.5}Te_{0.5}$, and $CdS_{0.25}Te_{0.75}$ alloys (in mV) compared to other values at different QD diameters (in nm) (Al-Douri *et al.*, 2015a).

QDs diameter	P_{QD} cal.	P_{QD} (Udipi *et al.*, 1996)
$CdS_{0.75}Te_{0.25}$		
61	0.1793	≤1
60	0.1804	
59	0.1815	
58.5	0.1825	
58	0.1833	
57.5	0.1840	
$CdS_{0.5}Te_{0.5}$		
63	0.5200	≤1
61.5	0.5212	
60.5	0.5222	
60	0.5232	
59	0.5240	
58	0.5247	
$CdS_{0.25}Te_{0.75}$		
65	0.1236	≤1
63.5	0.1248	
62.5	0.1259	
61.5	0.1268	
61	0.1276	
60	0.1284	

using Eq. (4.1). In Table 4.4, the calculated quantum dot potential at dot diameter dependence is computed.

Also as mentioned earlier, there is a value that separates the increasing and decreasing QDs potential called the critical dot diameter value. The correlation between dot diameter and transition pressure (P_t) is necessary to be calculated from the molar free energies difference. The ΔG_t refers to Gibbs free-energy difference between different tetrahedral compounds that is given by $P_t \Delta V/V_t$ (in kJ/mol). The energies are bigger for smaller bond lengths. The correlation between QD's potential and dot diameter is inverse as observed in Table 4.4 to confirm that the energy band positions are changed at the principal points (Γ→L, Γ→X, and Γ→Γ) of the Brillouin zone. The correlation between QDs potential and dot diameter (Table 4.4) is inverse as verified by Fig. 4.4. It is observed that there is a linear relationship for $CdS_{1-x}Te_x$ alloys, although there is a little fluctuation of QDs potential and the calculated results are in agreement with others (Al-Douri, 2009) that is an indication that the electrons are tunneling QDs.

The distinguished parameter in connection with the interactions of atomic microscopy is referred to as refractive index (n). Theoretically, there are two different principles in dealing with this topic: the first is refractive index that relates to the local polarizability and density; the second is refractive index that relates to dielectric constant dependent E_g (Al-Douri *et al.*, 2008). Therefore, there are different ways and attempts to relate the E_g and refractive index via specific relationships (Herve and Vandamme, 1994). Anyway, the incident photon energy and temperature dependent refractive index are noticed (Penn, 1962; Van Vechten, 1969; Ravindra *et al.*, 1979; Samara, 1983; Ghosh *et al.*, 1984; and Herve and Vandamme, 1995). The results are displayed in Fig. 4.5. The calculated refractive indices and the optical dielectric constants of the end-point compounds are investigated and listed in Table 4.5.

It is clear that the calculated n using the model of Herve and Vandamme (1995) is an appropriate one because the reflectivity parameter is important in enhancing the photoconversion for solar cells. Again, a linear dependence of the properties of the $CdS_{1-x}Te_x$ alloy on the dot diameter is observed, and the refractive index for small diameter dependence tends to shift toward the blue–green. It means a high

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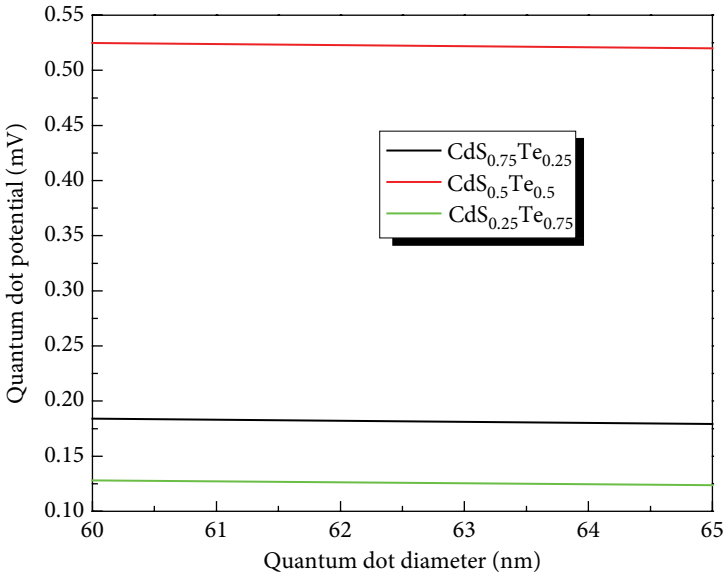

FIG. 4.4
QDs diameter dependence of the quantum dot potential for $CdS_{0.75}Te_{0.25}$, $CdS_{0.5}Te_{0.5}$, and $CdS_{0.25}Te_{0.75}$ alloys (Al-Douri *et al.*, 2015a).

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absorption and low reflection spectrum may be attributed to increasing solar cells efficiency. This work regards an impetus for researching further materials for both theoreticians and experimentalists to improve solar energy applications.

4.4.3 Chalcogenides

As mentioned earlier too, the covalent semiconductors of tetrahedral shape are fourfold coordinates and have low structure density, bounded nearest neighbors' atoms of sp^3 hybrids with a possibility of tuning E_g in terms of dot diameters. Table 4.6 presents the calculated E_g values of indirect ($\Gamma \rightarrow L$) and ($\Gamma \rightarrow X$), and direct ($\Gamma \rightarrow \Gamma$) E_g via EVGGA and mBJ to investigate dot diameters dependent for $PbS_{1-x}Te_x$ alloys compared to experimental (Strehlow and Cook, 1973) and theoretical results (Rached *et al.*, 2003; and Al-Douri *et al.*, 2015b). The mentioned values of ($\Gamma \rightarrow \Gamma$) E_g are overestimated in comparison to experimental ones due to specific considerations of employing EVGGA and mBJ approximations. So, $PbS_{1-x}Te_x$ alloys have been categorized as direct E_g semiconductors. The dot diameter dependent QDs potential is an important research and recommended for infrared light detection and generation applications. Hence, Table 4.6 displays the direct correlation of E_g and dot diameters as verified by Fig. 4.6.

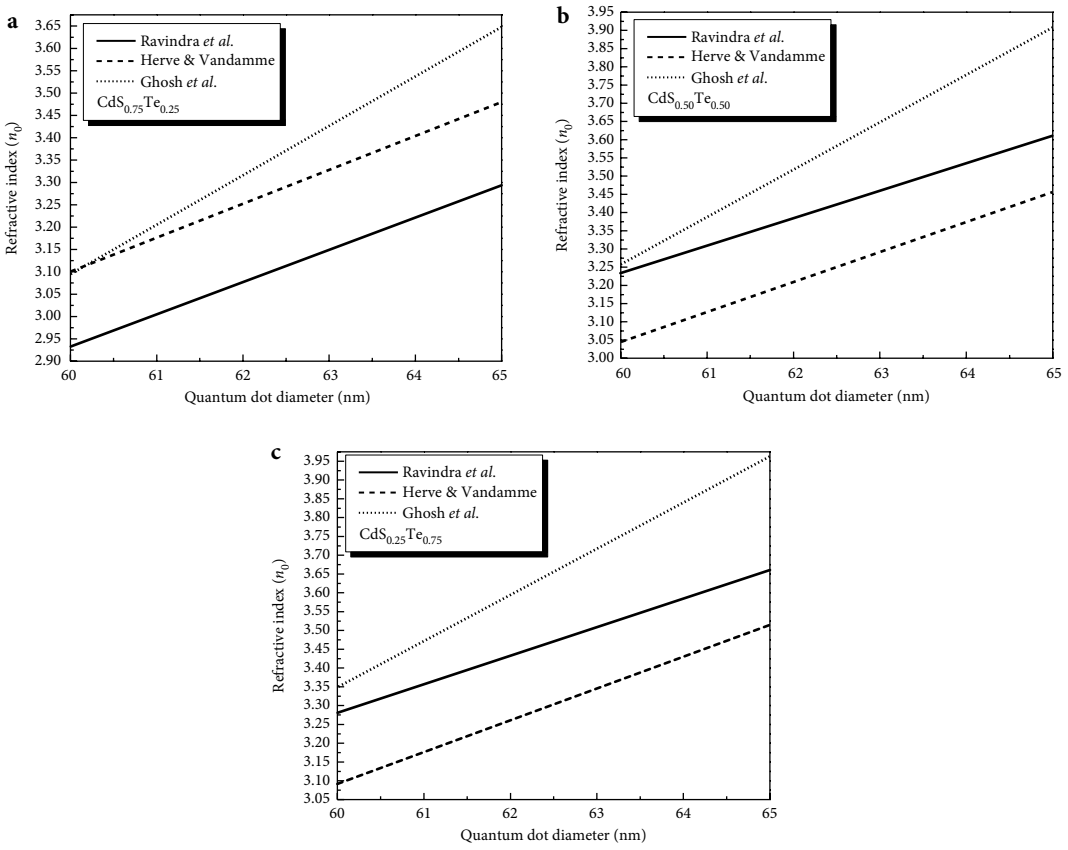

FIG. 4.5
QDs diameter dependence of the refractive index (n) for (a) $CdS_{0.75}Te_{0.25}$, (b) $CdS_{0.5}Te_{0.5}$, and (c) $CdS_{0.25}Te_{0.75}$ alloys (Al-Douri *et al.*, 2015a).

The FP-LAPW has been employed to compute E_g between conduction band minimum (CBM) at X and valence band maximum (VBM) at Γ. Our model (Al-Douri, 2009) has proved that QDs potential has been evaluated using Eq. (4.1). Table 4.7 presents dot diameter dependent calculated QDs potential. It is noticed that QD diameters are attributed to reproducing alloys randomness utilizing SQS Zunger's approach (Zunger *et al.*, 1990).

Also as mentioned earlier, there is a value that separates the increasing and decreasing of QDs potential called the critical dot diameter value. The correlation between dot diameter and transition pressure (P_t) is necessary to be calculated from the molar free energies difference. The ΔG_t refers to Gibbs free-energy difference between different tetrahedral compounds that is given by $P_t \Delta V / V_t$ (in kJ/mol).

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Table 4.5

Calculated refractive indices for $CdS_{0.75}Te_{0.25}$, $CdS_{0.5}Te_{0.5}$, and $CdS_{0.25}Te_{0.75}$ alloys at dot diameter dependence using Ravindra *et al.* (1979), Herve and Vandamme (1995), and Ghosh *et al.* (1984) models corresponding to optical dielectric constant (Al-Douri *et al.*, 2015a).

QDs diameter	*n*	ε_∞
CdS	2.589[a] 2.567[b] 2.611[c] 2.38[d]	6.702[a] 2.589[b] 2.817[c]
CdTe	3.345[a] 3.1627[b] 3.439[c] 2.7[d]	11.189[a] 9.998[b] 11.826[c]
$CdS_{0.75}Te_{0.25}$		
61	3.46[a] 3.28[b] 3.63[c]	11.97[a] 10.75[b] 13.17[c]
60	3.38[a] 3.20[b] 3.50[c]	11.42[a] 10.24[b] 12.25[c]
59	3.31[a] 3.12[b] 3.38[c]	10.95[a] 9.73[b] 11.42[c]
58.5	3.23[a] 3.05[b] 3.28[c]	10.43[a] 9.30[b] 10.75[c]
58	3.16[a] 2.99[b] 3.18[c]	9.98[a] 8.94[b] 10.11[c]
57.5	3.09[a] 2.93[b] 3.09[c]	9.54[a] 8.58[b] 9.54[c]
$CdS_{0.5}Te_{0.5}$		
63	3.59[a] 3.44[b] 3.89[c]	12.88[a] 11.83[b] 15.13[c]
61.5	3.51[a] 3.35[b] 3.73[c]	12.32[a] 11.22[b] 13.91[c]
60.5	3.44[a] 3.26[b] 3.60[c]	11.83[a] 10.62[b] 12.96[c]
60	3.37[a] 3.18[b] 3.47[c]	11.35[a] 10.11[b] 12.04[c]
59	3.29[a] 3.11[b] 3.36[c]	10.82[a] 9.67[b] 11.28[c]
58	3.22[a] 3.04[b] 3.26[c]	10.36[a] 9.24[b] 10.62[c]
$CdS_{0.25}Te_{0.75}$		
65	3.64[a] 3.50[b] 3.91[c]	13.24[a] 12.25[b] 15.28[c]
63.5	3.56[a] 3.40[b] 3.83[c]	12.67[a] 11.56[b] 14.66[c]
62.5	3.49[a] 3.32[b] 3.69[c]	12.18[a] 11.02[b] 13.61[c]
61.5	3.41[a] 3.23[b] 3.55[c]	11.62[a] 10.43[b] 12.60[c]
61	3.34[a] 3.16[b] 3.44[c]	11.15[a] 9.98[b] 11.83[c]
60	3.27[a] 3.09[b] 3.33[c]	10.69[a] 9.54[b] 11.08[c]

[a]Ravindra *et al.* (1979).
[b]Herve and Vandamme (1995).
[c]Ghosh *et al.* (1984).
[d]Ravindra *et al.* (1979) Expt.

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Table 4.6

Different QD diameters (in nm) dependent principal E_g for $PbS_{0.25}Te_{0.75}$, $PbS_{0.5}Te_{0.5}$, and $PbS_{0.75}Te_{0.25}$ alloys (in eV) in comparison with experimental and theoretical data (Al-Douri *et al.*, 2015b).

QDs diameter	E_g (Γ→Γ)		E_g (Γ→X)		E_g (Γ→L)	
PbS	1.2448[C1] 1.1888[C2] 0.286[a] 0.989[b] 0.069[c]		7.1691[C1] 6.786[C2]		5.2538[C1] 4.6518[C2]	
PbTe	1.2948[C1] 1.185[C2] 0.19[a] 0.5704[b] 0.032[c]		5.6827[C1] 5.1268[C2]		4.0139[C1] 3.8054C_2	
$PbS_{0.75}Te_{0.25}$	C_1	C_2	C_1	C_2	C_1	C_2
71	0.7895	0.9752	1.2505	1.4375	2.5299	2.678
73	0.9242	1.1681	1.3106	1.5433	2.53	2.7164
74	1.0012	1.2901	1.3355	1.6054	2.5004	2.7181
76	1.0461	1.3683	1.3414	1.6398	2.4573	2.6992
77	1.0682	1.42	1.3329	1.6576	2.4055	2.6697
78	1.0796	1.4509	1.3192	1.6615	2.3526	2.6317
$PbS_{0.5}Te_{0.5}$	C_1	C_2	C_1	C_2	C_1	C_2
69	0.8103	1.0532	1.2157	1.4425	2.6332	2.7619
71	0.9429	1.2492	1.2881	1.5677	2.6235	2.7972
73	1.0133	1.3622	1.3192	1.6367	2.5877	2.7937
74	1.0544	1.431	1.329	1.6734	2.5425	2.7717
75	1.0774	1.4737	1.326	1.6923	2.4935	2.7407
76	1.0891	1.4989	1.3156	1.6954	2.4435	2.703
$PbS_{0.25}Te_{0.75}$	C_1	C_2	C_1	C_2	C_1	C_2
68	1.0563	1.3687	1.4462	1.7495	2.9386	3.1281
69	1.1557	1.5321	1.4912	1.8491	2.9258	3.1614
71	1.2138	1.6326	1.5112	1.9053	2.892	3.1605
72	1.2447	1.6943	1.5121	1.9344	2.8463	3.1402
73	1.262	1.7321	1.506	1.9468	2.7941	3.1091
74	1.2611	1.7535	1.4868	1.948	2.7221	3.0677

[a]Strehlow and Cook (1973) exp.
[b]Rached *et al.* (2003) theo.
[c]Al-Douri *et al.* (2015b) theo.
C_1: calculated by EVGGA, C_2: calculated by mBJ.

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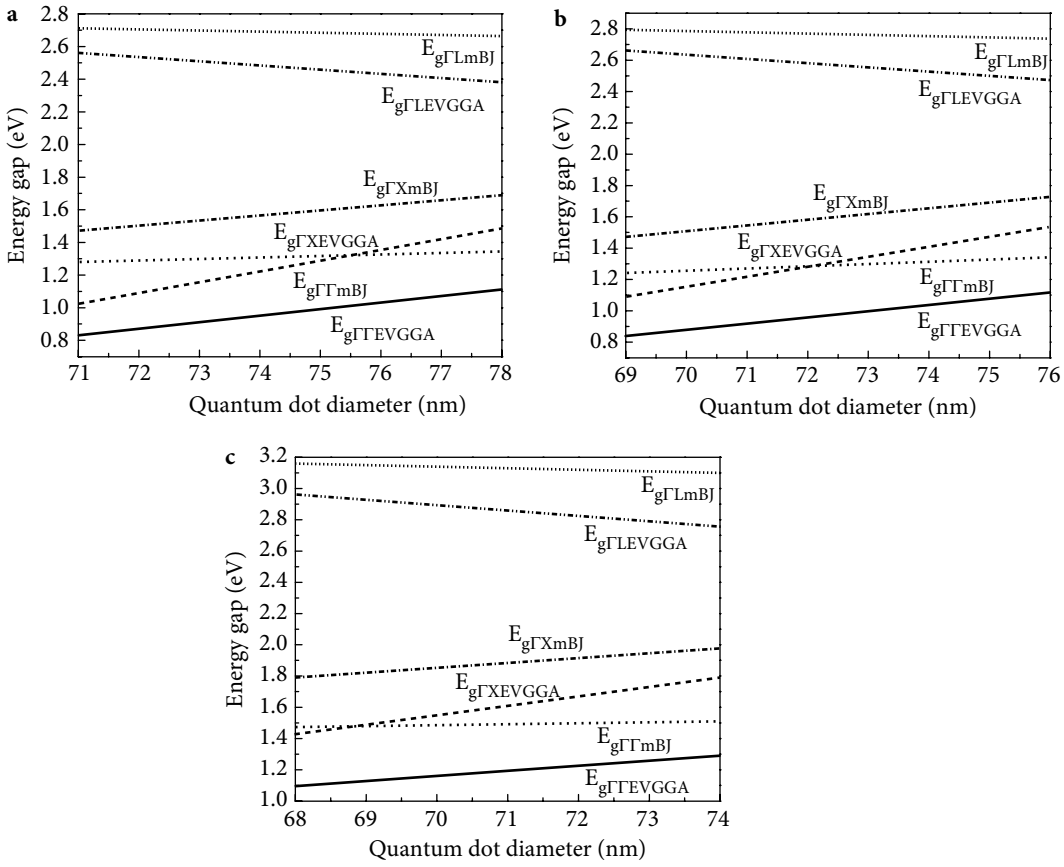

FIG. 4.6
QDs diameter dependent principal E_g for (a) $PbS_{0.75}Te_{0.25}$, (b) $PbS_{0.5}Te_{0.5}$, and (c) $PbS_{0.25}Te_{0.75}$ alloys (Al-Douri *et al.*, 2015b).

The energies are bigger for smaller bond lengths. The direct correlation between QD's potential and dot diameter is directly observed in Table 4.7 to confirm that the energy band positions are changed at the principal points (Γ→L, Γ→X, and Γ→Γ) of the Brillouin zone. The correlation between QDs potential and dot diameter (Table 4.7) is directly verified by Fig. 4.7. It is observed that there is a linear relationship for $PbS_{1-x}Te_x$ alloys, although there is a little fluctuation of QDs potential and the calculated results are in agreement with others (Balzaretti and da Jornada, 1996) that is an indication that the electrons are tunneling QDs.

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Table 4.7

The calculated quantum dot potential for $PbS_{0.75}Te_{0.25}$, $PbS_{0.5}Te_{0.5}$, and $PbS_{0.25}Te_{0.75}$ alloys (in mV) compared to other values at different QD diameters (in nm) (Al-Douri *et al.*, 2015b). C_1: calculated by EVGGA, C_2: calculated by mBJ.

QDs diameter	P_{QD} cal.		P_{QD} (Udipi *et al.*, 1996)
$PbS_{0.75}Te_{0.25}$	C_1	C_2	
71	0.450	0.555	≤1
73	0.526	0.658	
74	0.570	0.735	
76	0.596	0.779	
77	0.608	0.809	
78	0.615	0.827	
$PbS_{0.5}Te_{0.5}$	C_1	C_2	
69	0.461	0.600	≤1
71	0.537	0.712	
73	0.577	0.776	
74	0.601	0.815	
75	0.614	0.840	
76	0.620	0.854	
$PbS_{0.25}Te_{0.75}$	C_1	C_2	
68	0.602	0.780	≤1
69	0.658	0.873	
71	0.691	0.930	
72	0.709	0.965	
73	0.718	0.987	
74	0.719	0.999	

However, these relations of *n* are independent of temperature and incident photon energy (Penn, 1962; Van Vechten, 1969; Ravindra *et al.*, 1979; Samara, 1983; Ghosh *et al.*, 1984; and Herve and Vandamme, 1995). The correlation between refractive index and optical dielectric constant aside and QDs potential on another side is inversely investigated in Table 4.8 and shown in Fig. 4.8.

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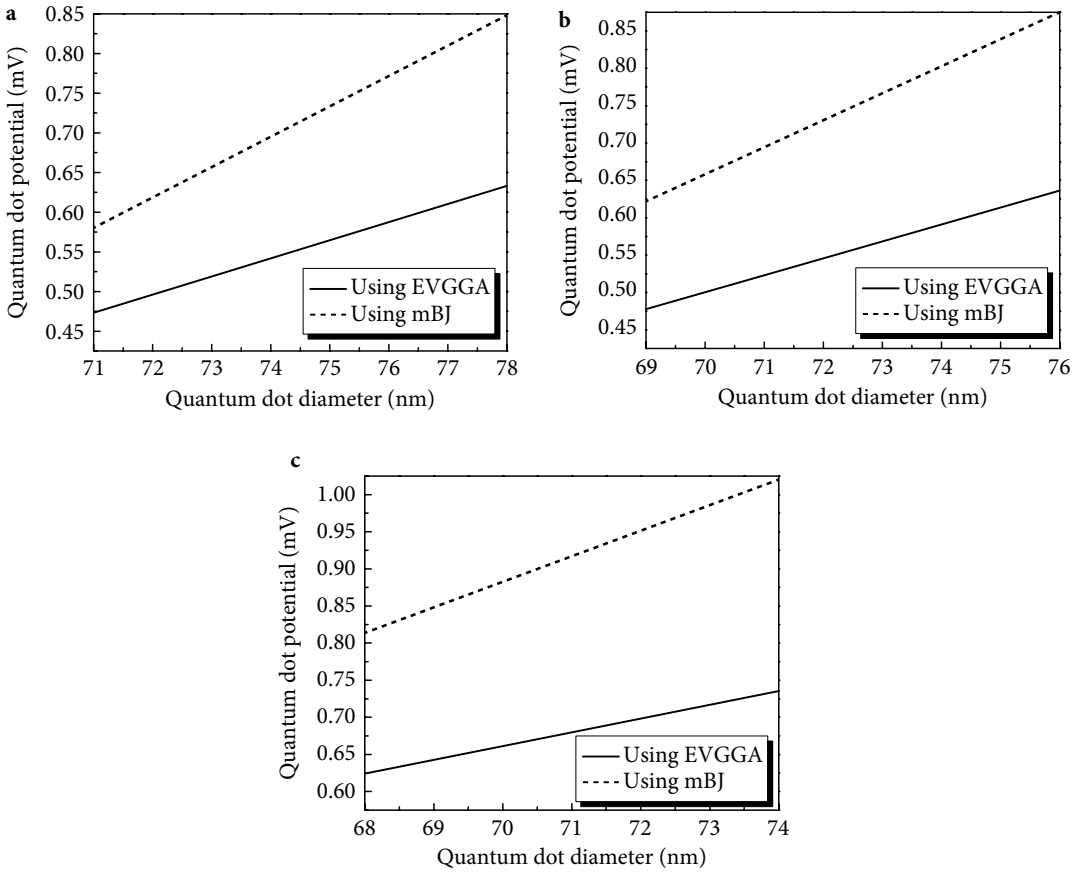

FIG. 4.7
QDs diameter dependence of the quantum dot potential for (a) $PbS_{0.75}Te_{0.25}$, (b) $PbS_{0.5}Te_{0.5}$, and (c) $PbS_{0.25}Te_{0.75}$ alloys (Al-Douri *et al.*, 2015b).

Ghosh *et al.* (1984) and mBJ approximation have been proved its appropriateness for n because reflectivity is necessary to enhance the conversion principle in solar cells. In addition, the QDs diameter dependent refractive index is linear for $PbS_{1-x}Te_x$ alloys. For smaller dot diameter, the refractive index is shifted to blue–green that is meaning higher absorption and lower reflection attributing to increased efficiency of solar cells.

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Table 4.8

QDs diameter dependent refractive index and optical dielectric constant for $PbS_{0.75}Te_{0.25}$, $PbS_{0.5}Te_{0.5}$, and $PbS_{0.25}Te_{0.75}$ alloys utilizing Ravindra *et al.* (1979), Herve and Vandamme (1995), and Ghosh *et al.* (1984) models (Al-Douri *et al.*, 2015b).

QDs diameter	*n*	ε_∞
PbS	3.27[a,f] 3.31[a,g] 3.09[b,f] 3.12[b,g] 4.26[c,f] 4.30[c,g] 4.16[d]	10.69[a,f] 10.95[a,g] 9.54[b,f] 9.73[b,g] 18.14[c,f] 17.30[c,g]
PbTe	3.24[a,f] 3.31[a,g] 3.06[b,f] 3.13[b,g] 6.22[c,f] 6.31[c,g] 5.98[e]	10.49[a,f] 10.95[a,g] 9.36[b,f] 9.79[b,g] 38.68[c,f] 39.81[c,g]
$PbS_{0.75}Te_{0.25}$		
71	3.55[a,f] 3.44[a,g] 3.39[b,f] 3.26[b,g] 4.68[c,f] 4.49[c,g]	12.60[a,f] 11.83[a,g] 11.49[b,f] 10.62[b,g] 21.90[c,f] 20.16[c,g,f]
73	3.47[a,f] 3.32[a,g] 3.30[b,f] 3.14[b,g] 4.54[c,f] 4.32[c,g]	12.04[a,f] 11.02[a,g] 10.89[b,f] 9.85[b,g] 20.61[c,f] 18.66[c,g]
74	3.42[a,f] 3.24[a,g] 3.24[b,f] 3.06[b,g] 4.66[c,f] 4.22[c,g]	11.69[a,f] 10.49[a,g] 10.49[b,f] 9.36[b,g] 21.71[c,f] 17.80[c,g]
76	3.39[a,f] 3.19[a,g] 3.21[b,f] 3.02[b,g] 4.43[c,f] 4.16[c,g]	11.49[a,f] 10.17[a,g] 10.30[b,f] 9.12[b,g] 19.62[c,f] 17.30[c,g]
77	3.38[a,f] 3.16[a,g] 3.20[b,f] 2.99[b,g] 4.41[c,f] 4.12[c,g]	11.42[a,f] 9.98[a,g] 10.24[b,f] 8.94[b,g] 19.44[c,f] 16.97[c,g]
78	3.37[a,f] 3.14[a,g] 3.19[b,f] 2.97[b,g] 4.40[c,f] 4.10[c,g]	11.35[a,f] 9.85[a,g] 10.17[b,f] 8.82[b,g] 19.36[c,f] 16.81[c,g]
$PbS_{0.5}Te_{0.5}$		
69	3.54[a,f] 3.39[a,g] 3.38[b,f] 3.21[b,g] 4.66[c,f] 4.42[c,g]	12.53[a,f] 11.49[a,g] 11.42[b,f] 10.30[b,g] 21.71[c,f] 19.53[c,g]
71	3.46[a,f] 3.27[a,g] 3.28[b,f] 3.09[b,g] 4.52[c,f] 4.25[c,g]	11.97[a,f] 10.69[a,g] 10.75[b,f] 9.54[b,g] 20.43[c,f] 18.06[c,g]
73	3.41[a,f] 3.20[a,g] 3.23[b,f] 3.02[b,g] 4.46[c,f] 4.16[c,g]	11.62[a,f] 10.24[a,g] 10.43[b,f] 9.12[b,g] 19,89[c,f] 17.30[c,g]
74	3.39[a,f] 3.16[a,g] 3.21[b,f] 2.98[b,g] 4.42[c,f] 4.11[c,g]	11.49[a,f] 9.98[a,g] 10.30[b,f] 8.88[b,g] 19.53[c,f] 16.89[c,g]
75	3.38[a,f] 3.13[a,g] 3.19[b,f] 2.96[b,g] 4.40[c,f] 4.08[c,g]	11.42[a,f] 9.79[a,g] 10.17[b,f] 8.76[b,g] 19.36[c,f] 16.64[c,g]
76	3.37[a,f] 3.11[a,g] 3.18[b,f] 2.95[b,g] 4.39[c,f] 4.06[c,g]	11.35[a,f] 9.67[a,g] 10.11[b,f] 8.70[b,g] 19.27[c,f] 16.48[c,g]
$PbS_{0.25}Te_{0.75}$		
68	3.39[a,f] 3.19[a,g] 3.21[b,f] 3.02[b,g] 4.42[c,f] 6.16[c,g]	11.49[a,f] 10.17[a,g] 10.30[b,f] 9.12[b,g] 19.53[c,f] 37.94[c,g]
69	3.33[a,f] 3.09[a,g] 3.14[b,f] 2.93[b,g] 4.33[c,f] 6.04[c,f]	11.08[a,f] 9.54[a,g] 9.85[b,f] 8.58[b,g] 18.74[c,f] 36.48[c,g]
71	3.29[a,f] 3.03[a,g] 3.11[b,f] 2.88[b,g] 4.28[c,f] 5.97[c,g]	10.82[a,f] 9.18[a,g] 9.67[b,f] 8.29[b,g] 18.31[c,f] 35.64[c,g]
72	3.27[a,f] 2.99[a,g] 3.09[b,f] 2.85[b,g] 4.26[c,f] 5.93[c,g]	10.69[a,f] 8.94[a,g] 9.54[b,f] 8.12[b,g] 18.14[c,f] 35.16[c,g]
73	3.26[a,f] 2.97[a,g] 3.08[b,f] 2.83[b,g] 4.24[c,f] 5.90[c,g]	10.62[a,f] 8.82[a,g] 9.48[b,f] 8.00[b,g] 17.97[c,f] 34.81[c,g]
74	3.25[a,f] 2.96[a,g] 3.07[b,f] 2.82[b,g] 4.23[c,f] 5.89[c,g]	10.56[a,f] 8.76[a,g] 9.42[b,f] 7.95[b,g] 17.89[c,f] 34.69[c,g]

[a]Ravindra *et al.* (1979).
[b]Herve and Vandamme (1995).
[c]Ghosh *et al.* (1984).
[d]Zemel *et al.* (1965) Expt.
[e]Weiting and Yixun (1990) Expt.
[f]Calculated by EVGGA.
[g]Calculated by mBJ.

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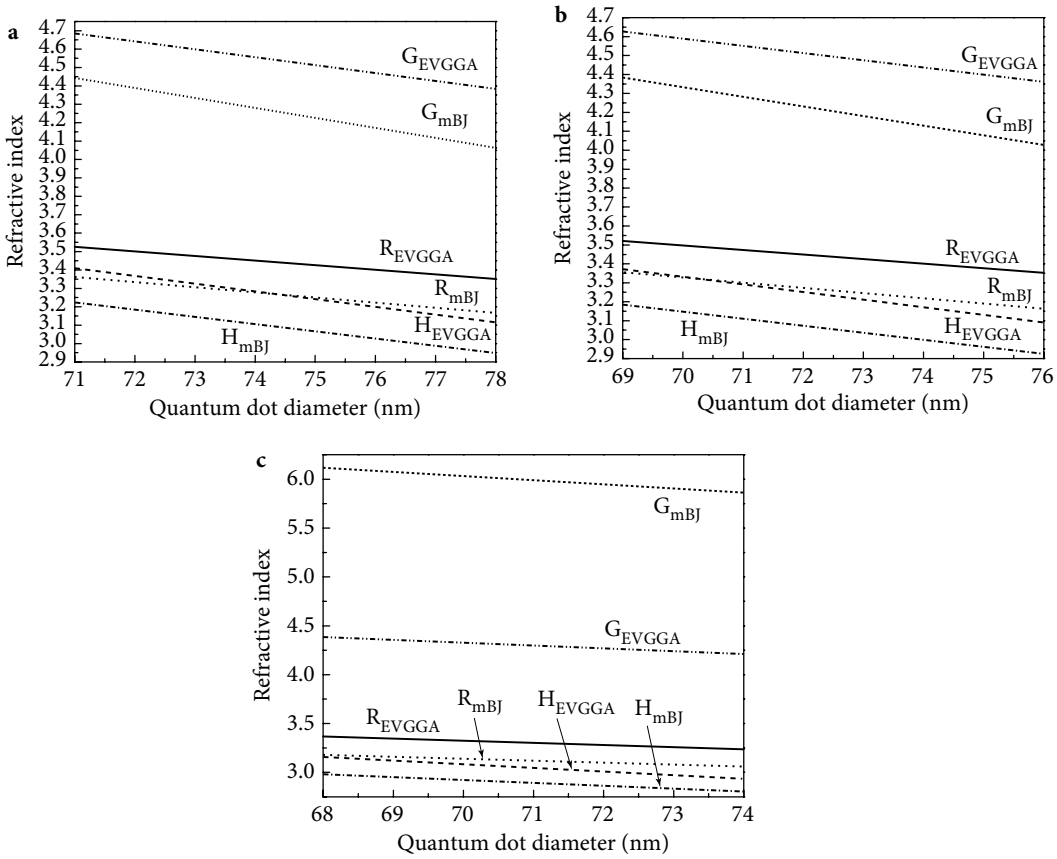

FIG. 4.8
QDs diameter dependent refractive index for (a) $PbS_{0.75}Te_{0.25}$, (b) $PbS_{0.5}Te_{0.5}$, and (c) $PbS_{0.25}Te_{0.75}$ alloys (Al-Douri *et al.*, 2015b). R: Ravindra *et al.* (1979), H: Herve and Vandamme (1995), G: Ghosh *et al.* (1984).

4.5 CONCLUSIONS

This work gives a comprehensive overview and understanding of nanotechnology applications in the renewable energy field. Nanotechnology has made a huge revolution in the size and design of renewable energy devices utilized for energy conversion and storage, environmental monitoring, as well as green engineering of environmentally friendly materials. It is shown that nanoelectronics play a significant role in human life by providing cheap and clean energy, which has now become a global industry. Some important conclusions are summarized:

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1. The use of nanomaterials in the renewable energy field can play a crucial role in increasing the efficiency of the solar cells.
2. Nanotechnology can improve them to reduce the environmental impact of burning fossil fuels to produce energy.
3. Nanotechnology makes a significant reduction in the cost of expensive components like solar cells as well as in the area of production and storage.
4. Nanotechnology can be considered a key to increase energy utilization.
5. Further research studies are necessary to study nanotechnology in all types of renewable energy.

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CHAPTER

5 FUNDAMENTALS OF SOLAR CELLS

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Ling, J., Wali, Q., Al-Douri, Y., and Jose, R., "Fundamentals of solar cells," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 5-1–5-26.

5.1 CONVERSION OF SOLAR ENERGY INTO ELECTRICAL ENERGY

One of the naturally occurring renewable energy processes is photosynthesis in plants, where energy is produced by absorbing solar light, carbon dioxide (CO_2), and water and chemically stored for future use as sugar (fuel). In terms of electronics, the final product of the conversion strategies would be electrical energy, given its versatility in diverse areas of human life. Undeniably, renewable sources are not continuous and could be intermittent, where energy is only generated when the source is present. In other words, they may be available when energy is not required or vice versa. Therefore, it is crucial to understand renewable energy as a dual topic of energy conversion and storage, with the energy generated when the sources are available and stored until they are utilized. This chapter discusses the fundamentals of the solar-to-energy conversion device, known as solar cells or photovoltaics, where readers are redirected to other reading materials for further understanding of the energy storage devices (Liang *et al.*, 2019, 2021; and Ling and Jose, 2021).

5.1.1 Types/generations of solar cells

The conversion of solar energy into electrical energy has been a fascinating subject because of the enormity of the source. More solar light reaches the Earth in an hour (4.3×10^{20} J) than the entire energy consumed in a year (4.1×10^{20} J) (although this may not remain true as new areas of energy usage emerge). The planet is unlikely to use more energy than it receives from the Sun, which makes the harvesting of solar energy extremely favorable in meeting the ever-growing energy demand. Besides, the whole process of solar-to-electric conversion does not involve any mechanical moving parts, allowing long time operation without the requirement of human interception for component replacement or

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maintenance. These benefits put solar energy ahead of other renewable energy technologies. The device to convert solar energy directly, without the need of moving mechanical parts, into electrical energy is called solar cells. The science and technology of solar cells are termed as photovoltaics. Solar cells are broadly classified into three generations, according to the material composition and a device parameter called "exciton diffusion length (L)" defined as $L = \sqrt{D_n \tau}$, where D_n is the exciton diffusion coefficient and τ is the exciton lifetime. The exciton diffusion length could be explained as the maximum distance that an exciton can travel before recombination occurs. The types of solar cells are as follows:

a. **First-generation solar cells**. They are made of single crystalline silicon. Owing to the low intrinsic absorptivity of silicon, crystals with a large thickness ($\sim$300 μm) are adopted for high absorption and the creation of large charge carrier density. To ensure a high charge extraction rate, the diffusion length of the exciton, in this case, needs to be $\geq$300 μm. However, extreme material purity is required to offer such large diffusion lengths, and developing high purity silicon single crystals is expensive. Over the years of research to reduce the thickness of the silicon single crystals in solar cells, the state-of-the-art silicon solar cells employ a 200 μm thick crystal. In addition to silicon, compound semiconductors such as GaAs and InP are also employed in first-generation solar cells. Among all its counterparts, silicon solar cells attracted the most attention owing to their abundance, which guarantees lower cost. In fact, monocrystalline silicon is currently the major photovoltaic market player. Currently, the efficiency of the silicon solar cells has been enhanced to 60% by using light concentrators to focus the solar irradiance onto the solar cells, subjecting the semiconductor to a solar illumination equivalent to $>$100 suns.
b. **Second-generation solar cells**. Different from their first-generation counterparts, second-generation solar cells adopted thin-film light absorbing materials, also known as thin-film solar cells, with an exciton diffusion length of $\sim$1 μm. Such low thickness offered flexibility to solar cell devices. Second-generation solar cells can also be developed from mono-crystalline silicon solar cells with very low thickness. Other materials employed in the second-generation solar cells include polycrystalline and amorphous silicon and compound semiconductors such as CdTe and CuInGaSe. Even though numerous attempts have been devoted to further reducing the film thickness, thus far, they were not successful due to high recombination in the lower size domains. To overcome this drawback, multiple layers of thin-film III–V semiconductors with different bandgaps are deposited on top of each other, resulting in a heterojunction device architecture. The heterojunction device architecture widened the absorbed wavelength range, which increases the efficiency of the thin-film solar cells, with an efficiency as high as 39.2% under one sun illumination reported back in 2020 by the National Renewable Energy Laboratory (NREL). However, stacking different semiconductors is not a straightforward process and usually ends in severe lattice mismatch, generating defects that are detrimental to photovoltaic performance. Currently, thin-film solar cells are mostly deployed in space industries as the energy generator for satellites.
c. **Third-generation solar cells**. The development toward third-generation solar cells, with an exciton diffusion length of $<$100 nm, was initiated for low-cost photovoltaic technologies. An exciting opportunity of the third-generation solar cells is their solution processability and less dependence

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on impurities but viability to large scale production such as roll-to-roll processing and printing (Fakharuddin *et al.*, 2014a). These advantages offer much cheaper third-generation solar cells than the first- and second-generation solar cells, which required rigorous material purification and highly controlled materials development methods, such as single crystal growth and vapor deposition processes for highly crystalline thin films, etc. Besides, another exciting opportunity in the third-generation solution processable solar cells is their workability in low-light conditions, whereas the others require high-intensity light for their operation. The third-generation solar cells aroused commercial interest because of nanostructured materials, which are either using scaffolds to host the primary light absorbing molecules or as charge selective layers. Most molecular absorbers, such as dyes (Grätzel, 2003, 2005), quantum dots (Wang, 2012; and Klimov, 2017), or semiconducting polymers (Ogawa, 2015; and Qiao and Iniewski, 2017) are the light absorbers in the third-generation solar cells. In this way, the exciton diffusion length is reduced to a few tens of nanometers. Dye-sensitized solar cells (DSSCs), quantum-dot solar cells (QDSCs), polymer solar cells, and perovskite solar cells (PSCs) are common examples. Among them, PSCs attracted the most attention due to their exceptional exciton diffusion length >100 μm (Zhang *et al.*, 2017), offering superior photovoltaic performance compared to their counterparts.

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5.1.2 Principle of solar cells and classification

Solar cells have primarily three fundamental processes, viz., (i) absorption of light by the photoactive material, (ii) creation of charge carriers, either as free electrons and holes or as bound excitons (the excitons are quasiparticles, constituting an electron and a hole confined in a single material), and (iii) the selective collection of electrons and holes at the respective charge collecting electrodes. The efficiency of a solar cell in collecting electrons and holes at the two ends of the device will generally determine the generated current per unit area, also known as photocurrent density. The one-dimensional photocurrent density ($J_n(X)$) in a solar cell, generally applicable in any electronic device, can be expressed as

$$J_n(X) = n(X)\mu(X)\nabla E_F. \tag{5.1}$$

In the above equation, $n(X)$ is the one-dimensional electron density, $\mu(X)$ is the electron mobility, and ∇E_F is the gradient in Fermi energy (difference in electrochemical potential between two materials across the electron flows). As the voltage has the dimensions of energy, the photovoltage in solar cells is proportional to ∇E_F . Semiconducting materials are the choice to build solar cells because of their electronic bandgaps that enable the absorption of more solar light, or a package of energy known as the photon, than metals and insulators. Metals have no bandgap and, therefore, do not absorb light. Insulators, on the other hand, only absorb light of high energy (ultra-violet region) and very low electron mobility ($<10^{-5}$ cm^2 V^{-1} s^{-1}) and, therefore, have poor electrical conductivity ($<10^{-10}$ S cm^{-1}). The electronic structures for metal, semiconducting, and insulating materials are simplified in Fig. 5.1. According to Eq. (5.1), high photocurrent could be drawn from a solar cell if it is constructed by semiconductors of a large difference in Fermi energy, high charge mobility, and high charge density. Although Eq. (5.1) helps to construct the functional diagram of solar cells, to understand the primary

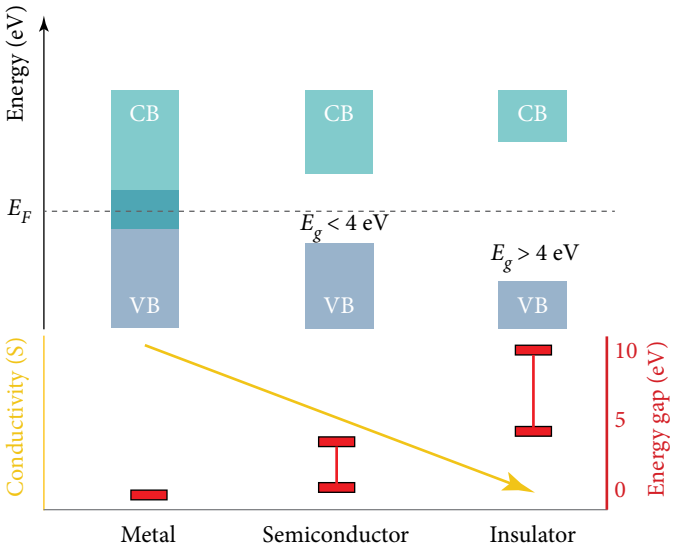

FIG. 5.1
The electronic structure of the metal, semiconductor, and insulator. The valence and conduction bands of the metal overlapped each other, offering high conductivity whereas bandgap exists in both semiconductor and insulator materials. The conductivity of materials is directly proportional to the energy gap between the conduction and valence bands.

process of the photoelectric conversion process, we need to understand the process of electron excitation, within the bandgap, on the absorption of sufficient light energy. Light can be viewed as a package of energy, known as the photon, where those with higher frequency have higher energy, a relation that can be summarized into

$$E = h\nu = \frac{h \cdot c}{\lambda}, \tag{5.2}$$

where E is the amount of photon energy; h is Planck's constant (4.136×10^{-15} eV s^{-1}); ν, c and λ is the frequency, speed, and wavelength of the incoming light. When the photon strikes a semiconductor, two possible scenarios could happen: (i) photons with energy smaller than the bandgap will transmit through the materials without exciting electrons and (ii) photons with energy equal or greater than the bandgap will be absorbed by the valence electrons and get excited to the conduction band (Fig. 5.2). To further improve the performance of the solar cells, the electrical conductivity and carrier density of the semiconductor can be further manipulated through doping, a process of intentionally introducing impurities into the crystal structure [Figs. 5.3(a)–5.3(c)]. Such a doping process is a norm in silicon semiconductors for both photovoltaic and transistor applications. Silicon element has four valence electrons, which are shared with four other silicon elements to achieve charge neutrality.

To understand the success of silicon solar cells, we have to take things to another height—combining both n-type and p-type doped silicon semiconductors into one single material. When both the n-type and p-type doped silicon are put into contact, a p-n junction is obtained. The band bending of both the valence and conduction bands occurs across the p-n junction as illustrated in Fig. 5.3(d). The band-bending within the p-n junction reports lower charge recombination, improves charge separation, and enhances charge collection. As shown in Fig. 5.3(d), the conduction band of p-type silicon has energy higher than that of n-type silicon, prompting the excited electron to diffuse to the latter, while the hole diffuses to the valence band of the former. Both the electron and the hole then travel across the external circuit, generating a photocurrent. Another factor leading to the success of silicon solar cells is its indirect bandgap [Fig. 5.4(a)], giving rise to a long excitation lifetime. A similar principle

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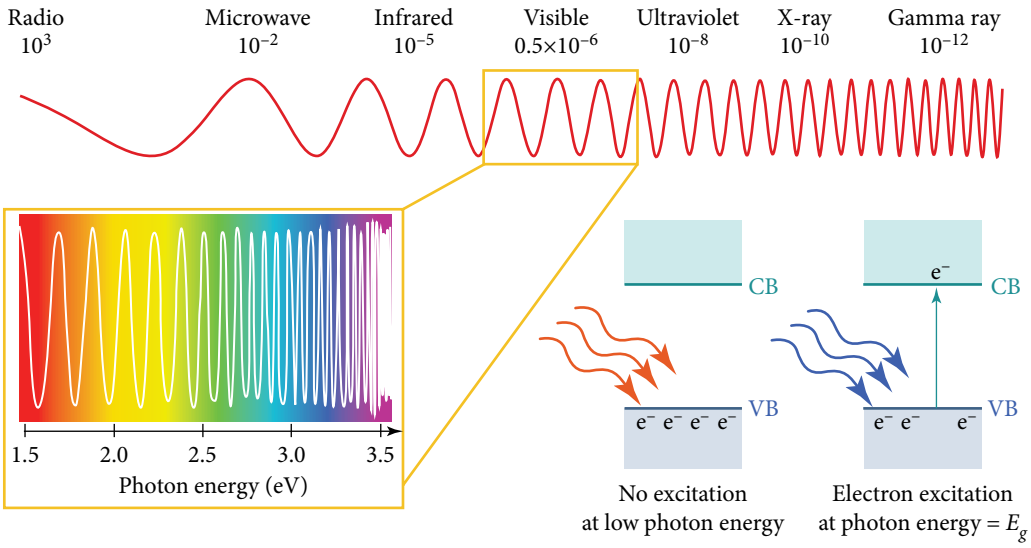

FIG. 5.2
The relationship between the frequency and photon energy of the electromagnetic wave. For a semiconductor with a bandgap of 1.5 eV, no valence electron will be excited when struck by a photon with an energy of $<$1.5 eV. The valence electron will only be excited when it absorbs a photon with an energy of $\geq$1.5 eV.

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is adopted in thin-film solar cells. However, instead of doping the semiconductors, band-bending was achieved by combining semiconductors with different chemical composites (different electronic structures) as shown in Fig. 5.4(b). However, these semiconductors were mostly of direct bandgap, offering a high absorption coefficient at extremely small thickness. Basically, third-generation solar cells also evolved based on a similar photoelectric conversion principle and will be further discussed in Sec. 5.2.

5.1.3 Characterization techniques for solar cells

Numerous techniques are reported to be efficient in characterizing solar cells and their components. In this section, only the techniques capable of characterizing the photovoltaic performance of solar cells are discussed. Among these techniques, three characterization methods are mainly used to characterize the photovoltaic performance of the solar cells, viz., photoelectric current (I–V) measurement, electrochemical impedance spectroscopy (EIS), and incident photon-to-current efficiency spectroscopy (IPCE).

a. **Photoelectric current measurement (I–V curve)**. The electrical output power of solar cells is calculated from the photoelectric current measurement. To compare solar cells characterized in

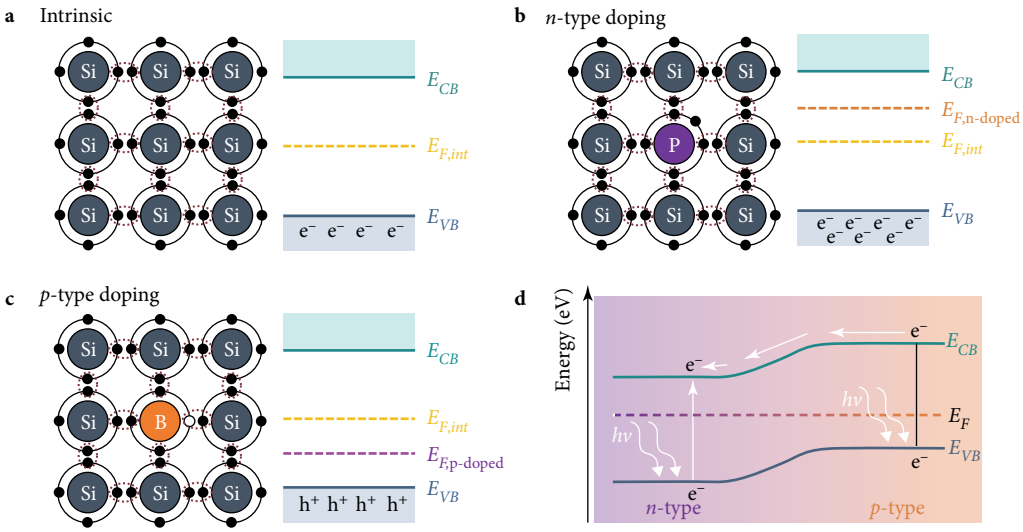

FIG. 5.3
The crystal and electronic structures of (a) intrinsic silicon semiconductor, (b) n-type doped silicon with trivalent boron element, and (c) p-type doped silicon with pentavalent phosphorus element. Both n-type and p-type doping induced extra electrons or holes, respectively, resulting in the realignment of Fermi energy level. (d) The band-bending phenomenon across the p-n junction when both the n-type and p-type semiconductors are placed in contact.

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different laboratories all over the world, photoconversion efficiency (PCE) is measured under a set of standard conditions. Essentially, these conditions specify that the temperature of the cell should be 25 °C and that the solar radiation incident on the cell should have a total power density of 1000 W m^{-2}, with a spectral power distribution, characterized as AM 1.5G. The photovoltaic parameters are an open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}), fill factor (*FF*), and PCE. A typical I–V curve of the sensitized solar cell is shown in Fig. 5.5.

In general, the V_{OC} is proportional to the Fermi energy gradient (∇E_F). However, the V_{OC} is dependent on the recombination rate in addition to the sensitizer and its adsorption mode. The sensitizer's adsorption geometry induces a substantial downshift of the conduction band energy of the metal oxide, thereby reducing the V_{OC}.

The J_{SC} is the current per unit active area of the device when the applied potential across the device is zero, i.e., I_{sc}/A, where both I_{sc} and A are the short-circuit current and active area, respectively. Under standard conditions, the J_{SC} is determined by (i) the amount of dye anchored onto the metal oxide or carrier density in light absorbing materials, (ii) absorption coefficient of the light absorbing materials, (iii) carrier extraction efficiency or charge recombination rate, and (iv) the electrochemical properties of the mesoporous network in the presence of an electrolyte.

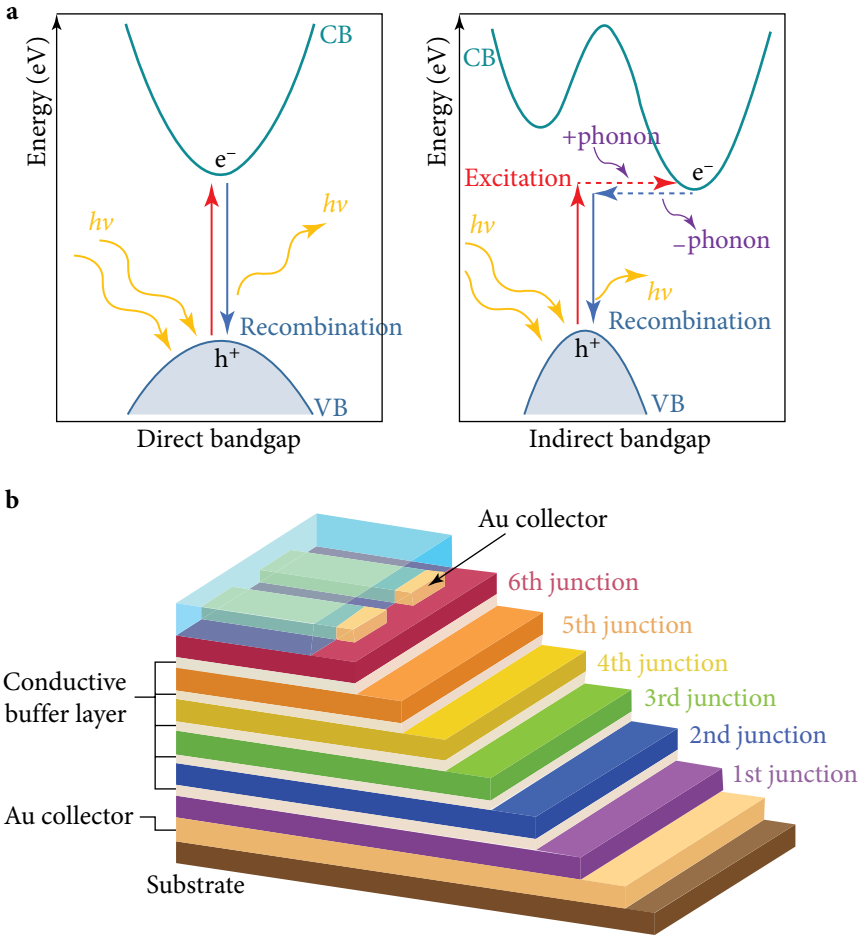

FIG. 5.4
(a) The difference between the direct (left) and indirect (right) energy gap structure as well as their electron excitation and recombination process. Indirect bandgap requires a phase change in electron through the non-radiative recombination (release of photons in the form of lattice vibration), before the radiative recombination. Such indirect charge recombination prolongs the lifetime of the exciton, favorable for charge extraction. (b) A schematic of heterojunction thin-film solar cells where different junctions absorb a different range of visible light, offering efficiency >40%.

The *FF* measures the ideality of the device and is defined as the ratio of maximum power output to the product of V_{OC} and J_{SC}, simplified as follows:

$$FF = \frac{P_{MAX}}{P_{Total}} = \frac{J_{MAX} \cdot V_{MAX}}{J_{SC} \cdot V_{OC}}. \tag{5.3}$$

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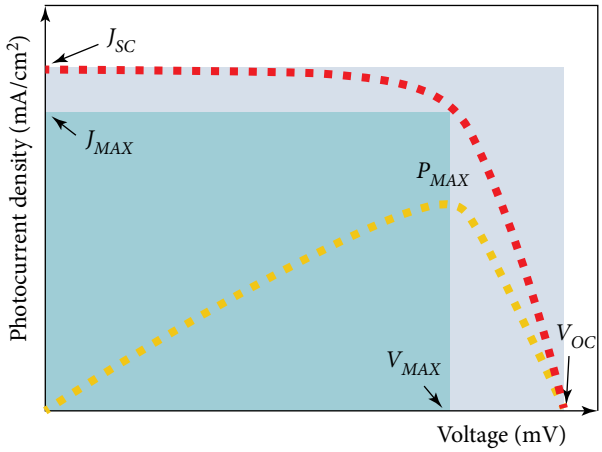

FIG. 5.5
The photovoltaic–current measurement (I–V curve) for a solar cell. The J_{MAX} and V_{MAX}, parameters useful in fill factor calculation, can be obtained from the point of P_{MAX} as shown in the figure. The point for V_{OC} and J_{SC} is demonstrated, respectively.

The *FF* is a measure of decrease in photocurrent with an increase in photovoltage and could be qualitatively determined from the squareness of the I–V curve (Fig. 5.5). Ideally, the power generated within the cell should dissipate at the external circuit. Parallel current paths such as electron back transfer and charge recombination within the device are a few of the possible causes of poor fill factor. An ideal cell should offer high internal resistance (>1000 Ω) to these parallel currents, often characterized by a shunt resistance. The magnitude of shunt resistance can be determined from the slope of the I–V curve near the short-circuit current point. Another possible cause of poor fill factor is the magnitude of series resistance at the cell–external circuit junction.

The PCE is a tool to measure the degree of capability of a solar cell in converting solar irradiance into electrical energy. For example, a solar cell with PCE = 25% can convert 25% of the solar irradiance into electrical energy. Calculating from AM 1.5G standard, the solar cells could generate 250 W m^2 out from an input solar irradiance of 1000 W m^2. The PCE can be obtained by comparing the output power from the device to the input irradiance power or simplified as follows:

$$\mathrm{PCE} = \frac{P_{Out}}{P_{In}} = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_{In}}. \tag{5.4}$$

According to Eq. (5.4), higher V_{OC}, J_{SC}, and *FF* for lower solar irradiance are the key to increased efficiency.

b. **Electrochemical impedance spectroscopy (EIS)**. EIS is a useful tool to understand the kinetics of electrical transport in solar cells, especially in the case of third-generation solar cells where multiple components and interfaces (the contact area between two different components) were involved. Different from the photoelectric current measurement, which adopted direct current, EIS utilized alternating current of different frequencies to study the electro-kinetic of the solar cells. The impedance (resistance in alternating current) measured at a specific frequency is related to the electro-kinetic processes occurring at the timescales of an inverse frequency (i.e., frequency of 10 Hz, process timescale of 0.1 s). From the perspective of material density, the diffusion of ions or electrons in high-density materials is much lower than that of low-density analogs and, therefore, occurs over a longer timescale and is measured using a low-frequency range. Other than that, the

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perturbation in voltage is kept at its minimum (mostly at 10 mV) during the EIS measurement to ensure linear response for a more simplified measurement (Fig. 5.6). The DSSC can be viewed electrically as a combination of resistance and capacitors. In the transmission model as shown in Fig. 5.6, the R_{CT} is the charge-transfer resistance of the charge recombination process between electrons in the mesoporous metal oxide film and ions in the electrolyte; C_{MO} is the chemical capacitance of the mesoporous metal oxide film; R_T is the transport resistance of the electrons in the mesoporous metal oxide film; Z_d is the Warburg element showing the Nernst diffusion of ions in the electrolyte; R_{Pt} and C_{Pt} are the charge-transport resistance and double-layer capacitance at the counter electrode (platinized transparent conducting oxide, TCO plate), respectively; R_{TCO}

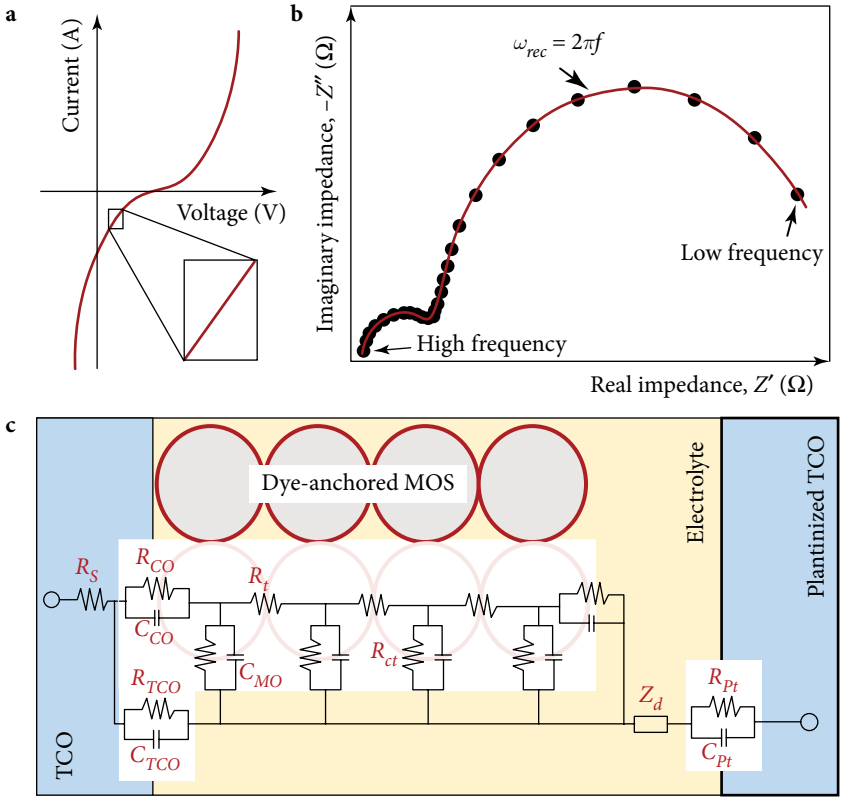

FIG. 5.6
(a) Linearity in the voltage–current relationship can be obtained by taking a small voltage window for linear electrochemical impedance spectroscopy. (b) A typical EIS spectrum, also known as the Nyquist plot, which can be used to measure both impedance and capacitance at the interface of each component. (c) Schematic showing the relationship between the materials in the DSSC and charge transport parameters in the diffusion-recombination model.

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and C_{TCO} are the charge-transfer resistance and the corresponding double-layer capacitance at the exposed TCO–electrolyte interface, respectively; R_{CO} and C_{CO} are the resistance and the capacitance at the TCO–TiO_2 contact, respectively; R_S is the series resistance, including the sheet resistance of the TCO glass and the contact resistance of the cell.

c. **Incident photon-to-current efficiency spectroscopy (IPCE)**. The IPCE or action spectrum is defined as the number of electrons flowing through the external circuit under short circuit conditions per incident photon at a given wavelength,

$$\mathrm{IPCE}(\lambda) = \frac{n_{electron}(\lambda)}{n_{photon}(\lambda)} = \frac{I(\lambda) \cdot h \cdot c}{P_{In}(\lambda) \cdot e \cdot \lambda}, \tag{5.5}$$

where $I(\lambda)$ is the measured current, $P_{in}(\lambda)$ is the input power, and λ is the wavelength of irradiation in nanometers. Figure 5.7 shows the typical IPCE curve, where current generated by the solar cells at a specific wavelength of irradiation can be obtained. Such measurement offers critical insight into the effective photon-to-current conversion range of specific light absorbing materials, allowing further device modification to widen the effective wavelength region as demonstrated in Fig. 5.7. The current calculated using Eq. (5.5) could also function as a validation technique to check the reliability of the photoelectric current measurement through comparison with the photocurrent. Undeniably, the capability of converting a photon into current is one of the intrinsic properties of

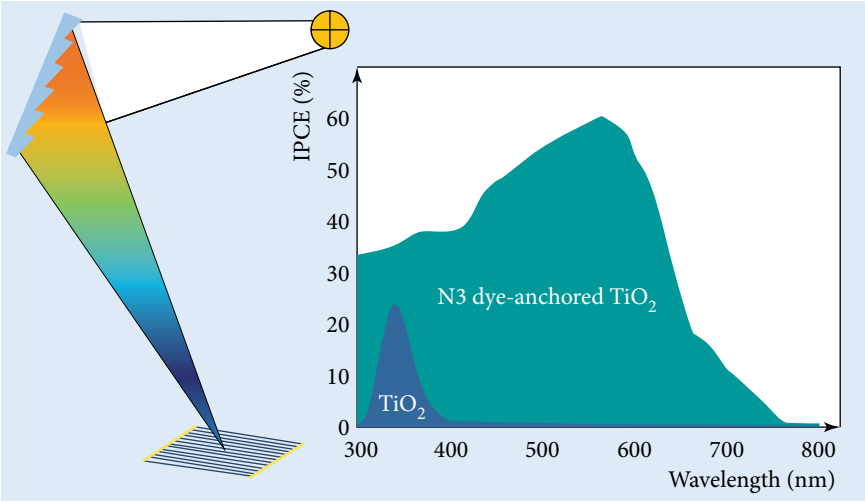

FIG. 5.7
A simplified IPCE instrument where light with different wavelengths is selected through a monochromator to study the current generated from the solar cells at different input wavelengths. The graph at the right schematically illustrated the difference between bare TiO_2 MOS and N3 dye-anchored TiO_2 MOS, showing the capability of N3 dye in extending the photon absorption range of the TiO_2 MOS.

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the light absorbing materials, where the range of wavelength that can be absorbed by the materials depends on the electronic bandgap of the semiconductor. In sensitized solar cells, this can be achieved through anchoring more light absorbing materials on a metal oxide with a highly specific surface area or through some bandgap modification techniques, which will be further discussed in Sec. 5.3.

5.2 PHOTOCONVERSION PROCESS IN THE SENSITIZED SOLAR CELLS

Similar to the first- and second-generation solar cells, sensitized solar cells also utilize semiconducting materials (either organic or inorganic) as the primary light absorbing materials. Figure 5.8 illustrates the spectra irradiance of photons from different wavelength regions, signifying the importance of solar cells to absorb and convert photons from the visible light region to achieve high photocurrent and excellent photovoltaic performance. To extend the photon absorption range down to the visible light region, photoanodes (which are wide bandgap semiconductors such as TiO_2, ZnO, and SnO_2) are sensitized with fluorophores such as organic dyes or quantum dots or a combination of both. Upon

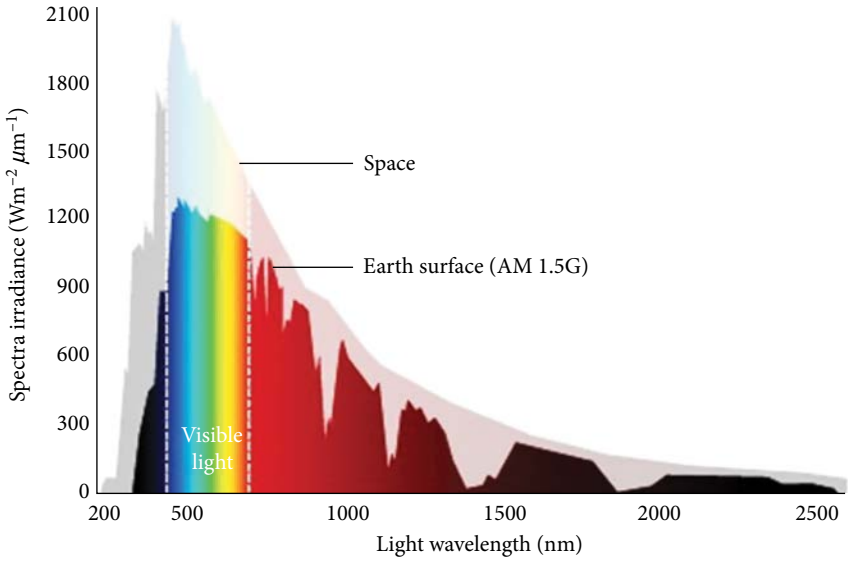

FIG. 5.8
The irradiance level of electromagnetic waves in the range of 200–2500 nm, ranging from the ultraviolet, visible to the infrared region. The spectra clearly show high irradiance in the visible light range, again highlighting the importance of a semiconductor to convert photons in the visible light region to achieve a high photovoltaic performance.

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illumination, the fluorophores absorbed photons from the visible light region, exciting electrons from its highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO), allowing the conversion of visible light photons that is previously an impossible task in non-sensitized photoelectrode.

In general, upon light absorption, Fermi energy of the fluorophore sensitized MOS goes up whereas that of the electrolyte remains at lower energies, thereby establishing a condition for current flow. Dye-sensitized solar cells (DSSCs) and quantum dot sensitized solar cells (QDSCs) are a few examples of this class of solar cells.

5.2.1 Device structure and working principle of sensitized solar cells

Figure 5.9 shows a typical functional diagram of a typical sensitized solar cell, taking a dye-sensitized solar cell (DSSC) as the prime example. The dye-anchored MOS is developed as a film on a conducting

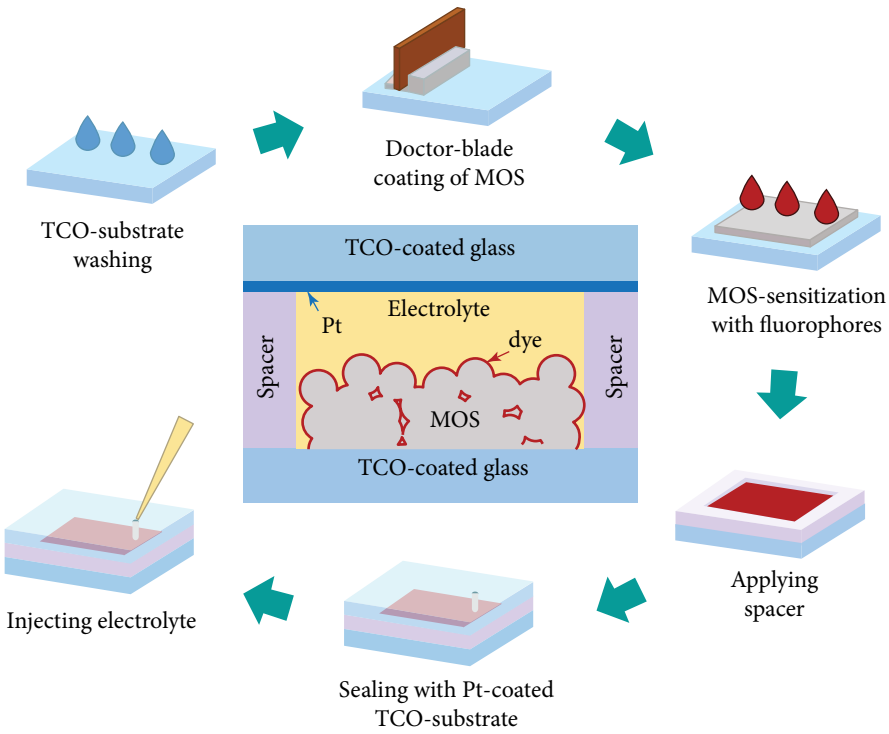

FIG. 5.9
The fabrication process and simplified device architecture of dye-sensitized solar cells (DSSCS).

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glass substrate (typically fluorine-doped tin oxide, FTO, or indium-doped tin oxide, ITO), which is called a photoanode or working electrode (WE). For flexible solar cells configuration, the dye-anchored MOS can be developed on ITO-coated polyethylene terephthalate (ITO/PET) polymeric films.

A simplified illustration of the working principle of a typical DSSC is provided in Fig. 5.10. When the light shines on the DSSC, electrons are excited from the HOMO to the LUMO of the anchored dye molecule. These excited electrons are then injected into the MOS and give rise to charge separation, resulting in the diffusion of electrons through the MOS. The electrons transported through the porous MOS could be moved through an external circuit via the FTO. To ensure an efficient electron extraction from the LUMO of the anchored dye molecule, the offset between the LUMO and conduction band of the MOS needs to be kept as minimum as possible. Once the electrons are injected into the conduction band of the MOS, the anchored dye molecules existed in a reduced state, with the hole staying at its valence band. For an electron to be excited again, the anchored dye molecules need to be regenerated and this is where electrolyte plays its role. An electron will be injected from the working potential of the electrolyte into the valence band of the anchored dye molecules, where the holes are said to be injected into the electrolyte. As a result, the anchored dye molecules are regenerated and ready for subsequent electron excitation upon illumination. The holes in the electrolyte then recombine with the electrons returning to the system after passing through the external circuit (load), regenerating the electrolyte. The overall process repeats continuously until the removal of the illumination source. However, it is to be noted that the electrolyte could permeate through the WE electrode film, reaching the FTO.

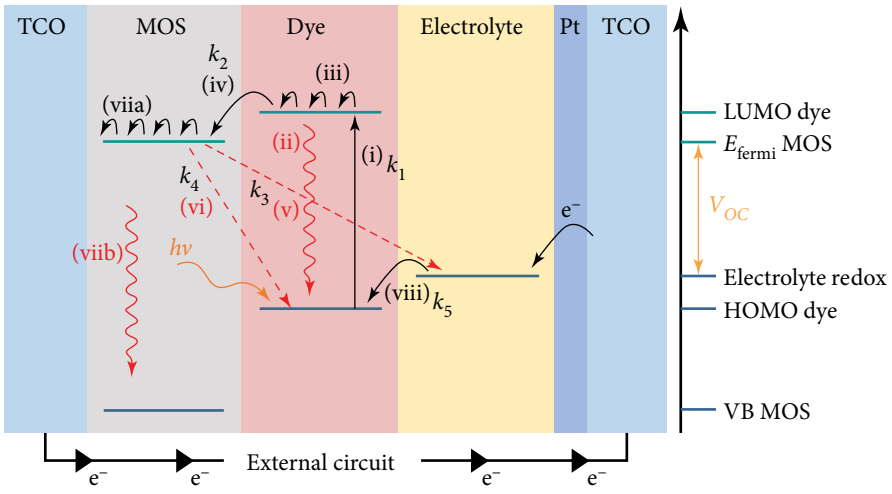

FIG. 5.10
The possible charge excitation, diffusion, extraction, and recombination processes in typical dye-sensitized solar cells, with each process detailed in the text.

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5.2.2 Processes and rate limiters in sensitized solar cells

As mentioned, on a few previous occasions, the electrons excited to the LUMO of the anchored dye molecules are constantly subjected to recombination prior to their transportation into the external circuit. Here, a few charge recombination routes are discussed to identify the rate limiters in sensitized solar cells, which are summarized in Fig. 5.10:

i. Light absorption. The amount of absorbed light depends on the absorption wavelength window of the dye and the intensity of solar irradiation at that window. The product of the absorption wavelength window and the molar absorption coefficient is the absorption cross section of the dye (α).
ii. Radiative recombination, i.e., the relaxation of the excited dye directly into its ground state, and its rate is constant (k_1). This process typically occurs in a timescale of several nanoseconds.
iii. Exciton diffusion length. Higher exciton diffusion length depicts a higher extraction rate prior to charge recombination.
iv. Interfacial electron transfer, i.e., injection of an electron from the dye to the photoelectrode, and its rate is constant (k_2). The interfacial electron transfer occurs typically in the timescale of several pico seconds.
v. Electron back transfer, i.e., the capturing of conduction band electrons by the oxidized species in the electrolyte, and its rate is constant (k_3).
vi. Interfacial charge recombination, i.e., the capturing of conduction band electrons by the oxidized dye molecules, and its rate is constant (k_4).
vii. Electron transport through the photoelectrode material controlled by (a) diffusion coefficient of electron (D_e) and (b) phono relaxation through which it loses its energy through electron–phonon interaction.
viii. The redox potential of the electrolyte and rate constant (k_5) of electron transfer to the oxidized dye.

Among these processes, interfacial charge transfer is three orders of magnitude faster than radiative recombination, i.e., $k_2/k_1 \sim 1000$, and electron back transfer is two orders of magnitude faster than interfacial charge recombination, i.e., $k_3/k_4 \sim 100$. Therefore, it is reasonable to assume that these two factors, i.e., radiative recombination and interfacial electron transfer, make negligible contributions to the final conversion efficiency. The exciton is highly localized in dyes and nanoclusters such as quantum dots that belong to a strongly confined regime, i.e., particle radius $<<$ exciton Bohr radius. In such cases, the exciton diffusion could be neglected. However, if extended structures such as quantum dots are in the weak confinement regime, i.e., particle radius$\sim$exciton Bohr radius, are used in the place of dyes, the exciton dynamics should also be considered. Therefore, the problem of eight rate limiting process is reduced into five for DSSC, viz., (i), (iv), (v), (vii), and (viii). Among the reduced five problems, (i), (vii), and (viii) are controlled by the light harvester (dyes or quantum dots), photoelectrode, and electrolyte, respectively; and (iv) and (v) are processes at the light harvester–photoelectrode and photoelectrode–electrolyte interfaces, respectively. It follows from the above

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description that the metal oxide photoelectrode participates in more than a number of processes than electrolytes and the dyes do and, therefore, they play a significant role in the final energy conversion efficiency of sensitized solar cells. Considering all the processes occurring within the sensitized solar cell, an expression for the photoconversion efficiency of solar cells can be quite complex. A generalized equation of state relating to the photoconversion efficiency (PCE) of sensitized solar cells with the process in it is proposed as follows (Muzakir *et al.*, 2013):

$$\mathrm{PCE} = f\left(\alpha\phi_i\eta_C\eta_r\right) \tag{5.6}$$

Relation (5.6) demonstrated that the photoelectric conversion efficiency is a function of α (cross section absorption of the sensitized electrode), ϕ_i (charge injection efficiency from the sensitizer to the working electrode film), η_C (charge collection efficiency at the working electrode film; a function of charge transport efficiency), and η_r (sensitizer regeneration efficiency). This once again clearly indicates that the mesoporous metal oxide network directly influences all these parameters. Thus, by reducing the losses in the mesoporous network, a better DSSC could be fabricated. Undoubtedly, both dye molecule and electrolyte also played an indivisible role in achieving highly efficient sensitized solar cells. However, given the limited space in this chapter, only the research efforts in the advancement of photoelectrodes are discussed here.

5.3 MAJOR DECISIVE COMPONENT IN SENSITIZED SOLAR CELLS—PHOTOELECTRODES

As explained in Sec. 5.2, photoelectrodes are at the heart of highly efficient sensitized solar cells. It has three main functions: (i) receive photoelectrodes generated at the excited states (or LUMO) of the anchored dye molecules, (ii) provide a larger surface area to anchor a large amount of dye molecules, and (iii) safely transport or extract the photoelectrons to the transparent conductive glass substrate (Archana *et al.*, 2010; Francis *et al.*, 2011; and Wali *et al.*, 2015a). The first function requires the conduction band of the photoelectrode to be at lower energies than the LUMO of the sensitizer whereas the second and third functionalities depend on a specific surface area and electrical conductivity of the nanostructured materials (Elumalai *et al.*, 2012; Kumar *et al.*, 2012; Bakr *et al.*, 2018, 2019; Ling *et al.*, 2019; and Pal *et al.*, 2019). The specific surface area and the inherent electron recombination from the radiative recombination between the excited electron at the conduction band and the resulting hole at the valence band could be evaluated from (i) the molecular weight of the material, (ii) orbitals composing the valence band and conduction band, and (iii) conduction band (electron) effective mass. To do such a first step evaluation, let us consider five metal oxide semiconductors, viz., TiO_2, ZnO, Nb_2O_5, SnO_2, and Fe_2O_3. The achievable surface area and charge transport properties can be evaluated from Table 5.1 (Fujihara *et al.*, 2007; Archana *et al.*, 2009; Le Viet *et al.*, 2010; Ahmed *et al.*, 2015; and Wali *et al.*, 2015b).

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Table 5.1
First step evaluation criteria of MOS for photoanode in sensitized solar cells.

MOS	Orbitals		Parity	Recombination rate	Molecular weight and surface area		Charge dynamics[a]	
	CB	VB			*M*	BET	*m**	μ
TiO_2	Ti (3d)	O (2p) + Ti (3d)	Dissimilar	Reduced	79.9	I	1–5m_o	0.1
Fe_2O_3	O (2p) + Fe (3d)	O (2p) + Fe (3d)	Similar	Increased	159.69	IV	1.6m_o	
ZnO	O (2p) + Zn (3d)	Zn (3d)	Dissimilar	Reduced	81.38	II	0.3m_o	200
Nb_2O_5	Nb (4d)	O (2p) + Nb (4d)	Dissimilar	Reduced	265.81	V	2.3m_o	0.07
SnO_2	Sn (5s + 5p)	O (2p)	Dissimilar	Reduced	150.71	III	0.27m_o	250

[a]*M* is the molecular weight, BET refers to the BET surface area in units of m^2/g, *m** is the effective mass, m_o is the electron rest mass; *m* is the charge mobility in units of $cm^2/V.cm$. Electron mobility and effective mass are related through the Lorentz relation.

Table 5.1 shows that the valence band of TiO_2 is composed of orbitals of different parity; therefore, the radiative electron recombination between the conduction and valence bands is suppressed due to Pauli's exclusion principle. It is a material of lower molecular weight and would provide a larger surface area and, hence, a large amount of sensitizer could be loaded onto it. However, TiO_2 has a relatively higher conduction band effective in mass making the electron to move slowly through it. Therefore, while looking at Eq. (5.1), TiO_2 provides both beneficial and sacrificial properties. In this scenario, materials such as ZnO could be a choice (providing a relatively large surface area and charge mobility). However, Zn in ZnO is divalent and could easily react with moisture, acidic groups in sensitizers anchoring group, etc. On the other hand, Fe_2O_3 has its conduction and valence bands made of orbitals of similar parity and facilitate radiative recombination. Besides, its molecular weight is also high. These are the scenario where materials such as SnO_2 and Nb_2O_5 offer higher charge mobility and suppresses electron recombination, but at the expense of a lower surface area. Fortunately, these drawbacks can be overcome through (i) the growth of vertical nanowires on a TCO substrate, (ii) the fabrication of core–shell structures, and (iii) band structure engineering.

5.3.1 Growth of vertical nanowires on TCO substrates

In nanoparticles, the charge diffusion is random whereas the diffusion is more ordered and directed if materials are grown as vertical nanowires on conducting glass substrates. Furthermore, the small nanoparticles are too small to support a macroscopic electric field to support a fast electron flow; whereas one of the dimensions of the vertical nanorods is macroscopic (i.e., length of the wire) and could support an electric field for a faster charge transport. See Fig. 5.11 for details. Consequently, vertical wires are shown to exhibit a high electron diffusion coefficient. However, they have inferior surface area; this limitation has been overcome by developing a particle film on top of the vertical nanorod film. See Fig. 5.12 for details.

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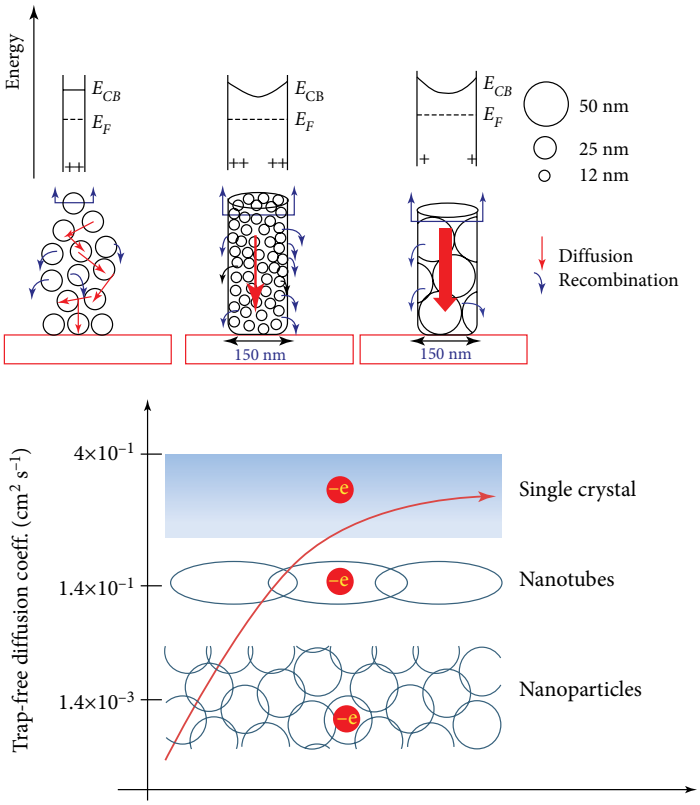

FIG. 5.11
(Top) A schematic showing the diffusion process in nanoparticle and nanowire systems. The bottom and top panels display the morphologies and energy levels, respectively. The red arrow indicates the diffusion process and the blue curves indicate the recombination processes. Three different structure designs are discussed; nanoparticles, nanorod with small primary nanoparticles, and nanorod with large primary nanoparticles. Reproduced with permission from Archana *et al.*, J. Phys. Chem. C **113**(52), 21538–21542 (2009). Copyright 2009 ACS Publications. (Bottom) Comparison of the trap-free electron diffusion coefficient in nanoparticle films and oriented polycrystalline nanotube arrays in DSSC with the diffusion coefficient values for a single crystal. Data extracted with permission from Villanueva-Cab *et al.*, Nano Lett. **14**(5), 2305–2309 (2014). Copyright 2014 ACS Publications.

5.3.2 Fabrication of core–shell structures

The rationale of a core–shell nanostructure as a photoanode for sensitized solar cells is to avoid recombination of the photoelectron with hole-conducting species in the electrolyte. In the core–shell nanostructure, the core forms a material of lower conduction band energy, and the shell is selected as a material with higher conduction band energy. The electron injection from the dye to the shell, then to its core is favored as shown in Fig. 5.13, whereas the recombination of electrons in the core with the electrolyte is energetically hindered (Jose *et al.*, 2009).

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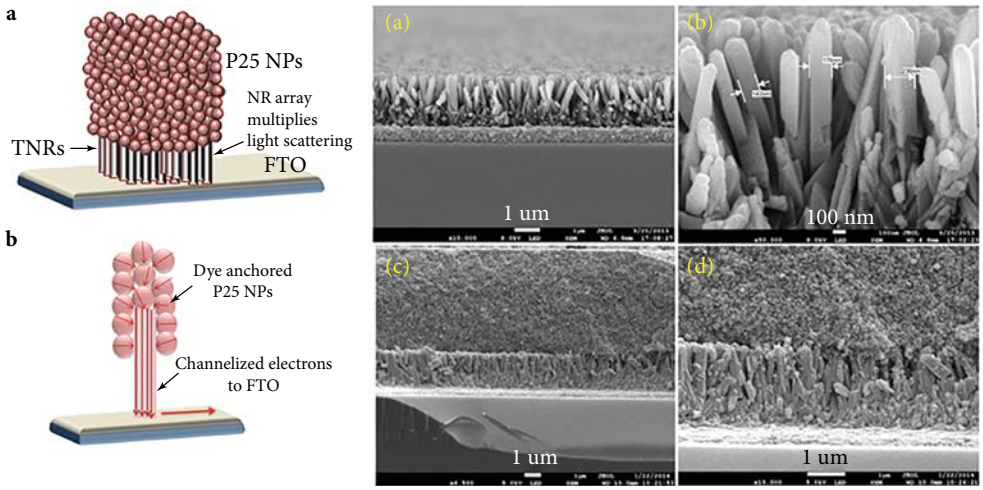

FIG. 5.12
(Left) Structure of the nanorod–nanoparticle (NR–NP) electrode; an isolated NR–NP configuration is in (b). The NRs facilitate the channelling of electron transport and improve the light scattering, while the NPs allow the anchoring of a large amount of dyes. (Right) Cross-sectional SEM images of NR and NR-NP films.

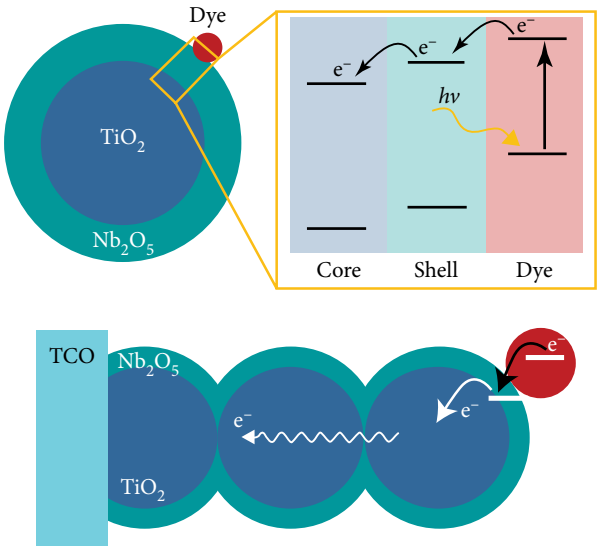

FIG. 5.13
Schematics and energetics of core–shell structures. The electrons in the core cannot recombine with the electrolyte because they need to pass through the shell material of a higher energy level, which is energetically prohibited.

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5.3.3 Band structure engineering

Band structure engineering refers to the removal of surface traps that occur in the bandgap of nanostructured semiconductors. Typically, these traps occur above the Fermi energy and as a result of surface defects. Therefore, the following method is adopted for removing surface traps (i) synthesizing highly crystalline nanostructured materials (Archana *et al.*, 2011; and Kumar *et al.*, 2012) and (ii) doping to uplift the Fermi energy level (Nair *et al.*, 2011; Elumalai *et al.*, 2012; and Kumar *et al.*, 2012). Uplifting the Fermi energy level also helps to boost the electrical conductivity of the MOS as revealed during the discussion on the effect of n-type doping on the electronic structure of silicon semiconductors. With enhanced electrical conductivity, excited electrons could be extracted more efficiently to the FTO, further inhibiting charge recombination.

5.4 RECENT PHOTOVOLTAIC DEVELOPMENT—THE RISE OF THIRD-GENERATION SOLAR CELLS

Without a doubt, the emergence of hybrid organic-inorganic perovskite solar cells (PSCs) boosted the competitiveness of the third-generation solar cells by delivering photoconversion efficiency (PCE) like the first two generations, but with a possibility of a lower cost owing to the relatively cheaper material processibility (Fakharuddin *et al.*, 2016; and Iftikhar *et al.*, 2021). The PSCs are fabricated by employing relatively simpler low-cost solution processing without the need for vacuum steps or expensive elevated temperature and can be fabricated on a variety of substrates (Fakharuddin *et al.*, 2015a, 2015b; Di Giacomo *et al.*, 2016; Mahmud *et al.*, 2018; Wali *et al.*, 2018a; and Farhadi *et al.*, 2019). Similar low-cost roll-to-roll production can be utilized to produce dye-sensitized or organic solar cells, making third-generation solar cells one of the most low-cost photovoltaic alternatives. Other than that, the possibility of developing third-generation solar cells into planar, flexible, wearable yarns, and transparent photovoltaic devices created a wide array of opportunities for the applications of third-generation solar cells.

5.4.1 Photoconversion process of perovskite solar cells

The photoactive material in PSCs is organic–inorganic hybrid perovskite (OIHP), which assumes the basic perovskite ABX_3 structure (Fakharuddin *et al.*, 2015c, 2017; and Wali *et al.*, 2020). In the ABX_3-type OIHP structure, A is an organic monovalent cation (methyl ammonium (MA^+, CH_3NH_3), formamidinium [FA^+, $CH_2(NH_2)_2$] with a 12-fold X ion coordination, B is a metal cation such as lead (Pb^{2+}), germanium (Ge^{2+}), or tin (Sn^{2+}) with sixfold coordination, and X is a halogen anion such as iodide (I^-), bromide (Br^-), and chloride (Cl^-). Inorganic halide perovskites with cesium (Cs^+) or rubidium (Rb^+) at the A-site are also reported (Mahmud *et al.*, 2018; Wali *et al.*, 2018b; Zabihi *et al.*, 2019; and Nwankwo *et al.*, 2020). The compelling features offered by perovskites are their light absorbing capability that creates charge carriers with long diffusion lengths and small

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effective masses; therefore, high charge mobility (Fakharuddin *et al.*, 2017). Many organometallic hybrid perovskite compounds have been tested in PSCs, which show dramatic performance on the laboratory scale: from a photo-conversion efficiency (PCE) of merely ~3.8% (the first embodiment of PSCs in 2009) to a record PCE ~25.2%, exceeding the PCE of the present photovoltaic (PV) market leader polycrystalline silicon while consuming ~1000 times less light harvesting material than silicon.

The concept of PSCs originated from the dye-sensitized solar cells, where the photoactive OIHP was used to replace the typical organic dye molecules. In 2009, Kojima *et al.* (2009) employed $CH_3NH_3PbI_3$ and $CH_3NH_3PbBr_3$ as sensitizers in a device with architecture similar to DSSC, which resulted in PCE ~3.81% and a significant high photovoltage (V_{OC} ~1 V). In a similar device architecture, Park *et al.* (Im *et al.*, 2011) optimized the m-TiO_2 layer's thickness and treated it with $Pb(NO_2)_2$ prior to the deposition that yielded PCE ~6.51%. However, these devices are unstable due to the rapid dissolution of the perovskite layer by the typical liquid electrolyte. The issue of rapid and abrupt degradation of the perovskite layer in PSCs by a liquid electrolyte was partially solved with the inclusion of a new synthesized solid-state hole transport layer (HTL) named as 2, 2′,7,7′-tetrakis (N,N′-p-dimethoxy-phenylamino)-9,9′-spirobifluorene (Spiro-OMeTAD) into the device (Kim *et al.*, 2012). The replacement of liquid electrolyte by Spiro-OMeTAD significantly improved the device stability under ambient conditions for about 500 h. Later, Lee *et al.* used insulating m-Al_2O_3 instead of conducting m-TiO_2 along with mixed $CH_3NH_3PbI_2Cl$ (Lee *et al.*, 2012), where m-Al_2O_3 was reported to act merely as a scaffold and does not take part in electrode extraction and transportation. The device based on m-Al_2O_3 termed as a meso-superstructured solar cell showed stable performance with PCE ~10.9%. It has shown that in alumina-based devices, the perovskite layer could function both as an absorber and n-type component, transporting electronic charges out of the device. This leads to the discovery of ambipolar transport properties (diffusion of both electrons and holes across the materials without any interference from each other) in OIHP, which offered many new opportunities in the development of perovskite solar cells. One of the benefits includes the elimination of m-TiO_2 at the expense of very little loss of PV parameters. Despite many attempts to eliminate m-TiO_2, this class of PSCs has shown the highest PCE >20% so far in a device structure similar to DSSC (with a significant reduction in the thickness of the m-TiO_2 layer from 10 μm to 300 nm). This study has been extended to various device designs by changing the orientation or tailoring the material's thickness, which includes mesoporous TiO_2 (m-TiO_2) with PCE >21% (Bi *et al.*, 2016), regular planar with PCE ~20.44% (Ding *et al.*, 2017), inverted planar with PCE ~19.9% (Wu *et al.*, 2017), meso-superstructure solar cells with PCE ~15.9% (Wojciechowski *et al.*, 2014), flexible device with PCE ~16.8% (Yoon *et al.*, 2017), hole transport layer free PSCs with PCE ~16.0% (Li *et al.*, 2015), electron transport layer free PSCs with PCE ~14.14% (Ke *et al.*, 2015), and fibre-shaped PSCs with PCE ~13.6% (Li *et al.*, 2016). More recently, PSCs are fabricated as woven and knitted textiles with PCE >10% (Li *et al.*, 2020; and Balilonda *et al.*, 2021). Nevertheless, the research on PSCs is intense and the above achievements will become history in the near future, with the commercialization of PSCs initiated by a few start-up companies at the end of 2010.

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5.4.2 Tandem photovoltaic

Tandem photovoltaic was introduced and gained considerable attention recently alongside the discovery of highly efficient PSCs owing to its possibility in offering efficiency higher than the 33.7% Shockley–Queisser limit. Figure 5.14 demonstrates an example of the perovskite/silicon tandem device where the bandgap of the PSCs subcell is fine-tuned to absorb light with a higher photon energy. The idea revolved around the technique to reduce thermalization loss in solar cells. As discussed in Sec. 5.2.2, when the valence electron absorbed a photon with energy equal to its bandgap, the electron is excited to the conduction band. However, when the valence electron absorbed the photon with energy far greater than its bandgap, the electron is excited to a delocalized state with a higher energy level than the conduction band. The electron is then relaxed back to the conduction band through non-radiative (release of phonon; crystal lattice vibration), a process known as thermalization loss. As a result, the excess photon energy is wasted. Through a finely tuned bandgap of the OIHP (E_g ~1.8 eV), the photon energy greater than the bandgap of silicon (E_g ~1.3 eV) is absorbed by the PSCs in photocurrent generation instead of being wasted in the single junction solar cells.

5.4.3 Up-scaling—module production

Even though numerous photovoltaic technologies had demonstrated high efficiency (PCE ≥15% for DSSC and QDSC, as well as PCE ≥25% for PSCs), the commercialization process of these devices is not that straightforward. The solar cells tested in a laboratory are usually fabricated in small size, with an active area of <1 cm², whereas the commercialized device needs to be fabricated into cells with an active area of >100 cm². These large cells are further connected to a solar module. One of the main bottlenecks is the synthesis process of nanostructured photoelectrode materials:

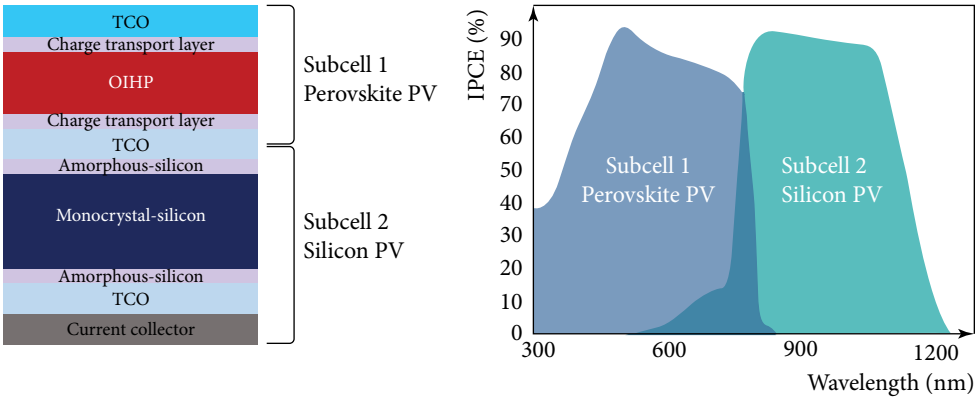

FIG. 5.14
Example schematic of perovskite/silicon tandem devices. Such devices significantly reduce thermalization loss and offer high incident photon-to-current efficiency at low wavelength (high energy) photons region.

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i. Nanoparticles can be synthesized in a large scale but there will be a very poor electron diffusion through it.
ii. Other morphologies offer superior charge transport properties but are not available in a large scale.

The first limitation severely reduces the photoconversion efficiency when the size of the device is systematically increased. The second limitation, on the other hand, would result in extremely costly devices when scaled up to an industrial scale. Besides the synthesis bottleneck of a nanostructured photoelectrode, the drop in photovoltaic performance of the sensitized solar cells when the active area is enlarged is another stumbling block toward commercialization. Such lowering in the photovoltaic performance is identified as the varied choice of diffusion path available in a large electrode film and this limitation was overcome by imposing a constraint on the electron motion in electrode films (Fakharuddin *et al.*, 2013). Through adopting novel photoelectrode designs, the lateral electron diffusion can be inhibited and allow a high electron extraction rate (Fakharuddin *et al.*, 2014b).

5.5 SUMMARY

A semiconductor of low bandgap ($\leq$1 eV) enables the absorption of the majority of solar light from the solar spectrum for making efficient solar cells. The light absorption either creates free charge carriers as in the first-generation solar cells or bound exciton as in the other generations. The free carriers are selectively collected using appropriate charge extraction layers, which are charge selective transporters. In the case of the formation of bound excitons, they are split into free carriers by a material interface, transported, and collected. For the flow of electrons to develop current, a gradient in Fermi energy is required, which in all solar cells is made via a material interface of different Fermi energies. The potential difference (open circuit voltage) offered by the solar cells is proportional to this Fermi energy and the drawable current (short-circuit current density) is the product of electron density, charge mobility, and gradient in Fermi energy. The first- and second-generation solar cells are already under practical application, whereas the third-generation solar cells are the ones that offer enormous potential for future applicability because of their solution processibility and workability in low-light conditions. One of the crucial factors of the commercialization of the third-generation solar cells is their inferior operational stability than the first- and second-generation devices.

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CHAPTER

6 WIND ENERGY

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6.1 INTRODUCTION

With the gradual depletion of global fossil fuels and the deterioration of the ecological environment, countries all over the world attach great importance to the utilization and development of clean energy to achieve a low-carbon economy (Tabassum-Abbasi *et al.*, 2014; and Luo, 2019). As one of the clean and renewable energy sources, wind power is the most potential and available renewable energy both commercially and technically (Goudarzi and Zhou, 2013), and it has the advantages of high energy conversion rate, large industrial scale (Guru *et al.*, 2010), and high social benefits (Kaplan, 2015; and Peng *et al.*, 2021).

Wind has a huge and destructive energy. The energy can be powerful enough to uproot trees and blow down power lines or even destroy buildings. Moreover, the storms can cause a wide range of vandalism and sometimes a national disaster. However, this energy can be transformed into beneficial power (electrical) by wind power plants (WPPs) (Kaldellis and Zafirakis, 2011). Therefore, the wind that we can feel streaming has to be harnessed and translated into a useful form of energy. The instrument that makes this change is a wind turbine rotor, which is attached to an electrical generator. Due to the wind energy formula, which is related to the cube of wind velocity, the power obtained from this phenomenon could be huge.

Renewable energy is becoming one of the major trends worldwide in the last two decades. Only in 2019, installation of 67 GW of wind energy and the same amount of solar energy were achieved globally (Ismaeel *et al.*, 2020). Due to the increase in the energy demand and due to the environmental challenges, the necessity of using renewable resources becomes more and more important. As a worldwide opinion, the use of fossil resources has a great impact on the phenomenon (global warming). The experts of the climate groups (Kaldellis and Zafirakis, 2011; and Abood *et al.*, 2021) think that keeping the emission of gases that warm our planet under certain levels should be paired with reducing the dependency on carbon in producing power by 80% by the year 2050 (Fleming and Probert, 1984). The technology of renewable energy (namely, the solar and wind energy) has grown significantly during the last two decades as shown in Fig. 6.1 (Fleming and Probert, 1984).

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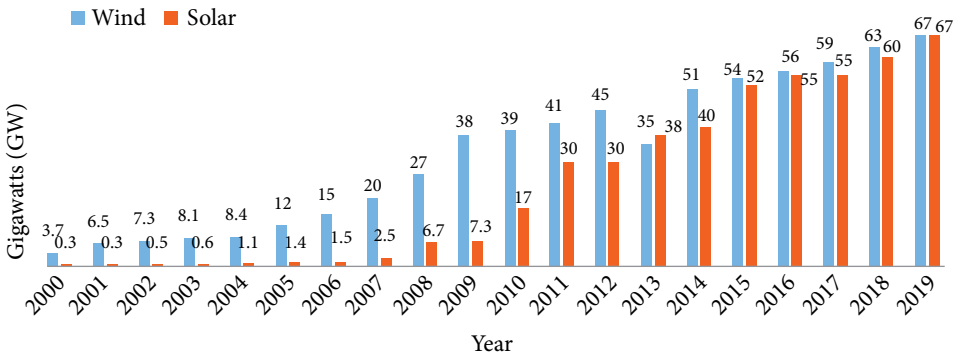

FIG. 6.1
Global cumulative installation 2000–2019 (Abood *et al.*, 2021).

On the global level of installing wind turbines, if we take the official data of year 2009 alone (Burton *et al.*, 2002; Manwell *et al.*, 2009, 2010; and Twidell and Weir, 2021), the world power capacity has increased by nearly 40 GW, reaching a total of 158 GW as shown in Fig. 6.2.

Wind exists everywhere on the earth and in some places with considerable energy density. Wind has been used in the past to generate mechanical power. Nowadays, wind power has become a promising

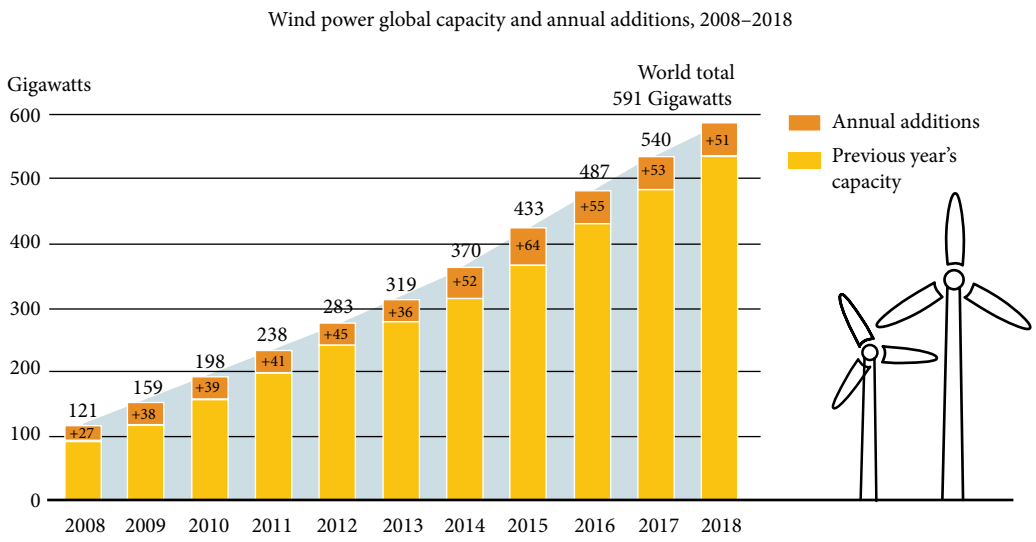

FIG. 6.2
Worldwide evolution in wind power capacity (Abood *et al.*, 2021).

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source to generate electricity because it is clean and efficient. It reduces acid rain, smog, and pollutants to the atmosphere. Renewable energy has become popular in recent years due to the need for the utilization of more environmentally friendly energy sources. In generating wind power, both the vertical axis wind turbines and the horizontal axis wind turbines play significant roles.

Wind energy is the conversion of wind kinetic energy into a useful form of energy, such as mechanical or electrical energy, that can be harnessed for practical use by using wind turbines. Basically, there are two types of wind turbines according to their axis of rotation to the ground, which are (Cheng *et al.*, 2012; and Wenehenubun *et al.*, 2015) as follows:

1. horizontal axis wind turbines (HAWTs) and
2. vertical axis wind turbines (VAWTs).

Each type has advantages and disadvantages. HAWTs are more common and widespread due to their high coefficient of performance and mechanical durability. Moreover, wind turbines can be divided according to their capacities to large wind turbines (LWTs) and small wind turbines (SWTs).

Wind energy is one of the cheapest and cleanest sources of renewable energy compared to all other known ones. The potential energy created by wind energy is plentiful and reduces greenhouse gas emissions if it supplants fossil fuel derived electricity. Wind turbine technology has lately been steadily improved.

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6.2 WIND ENERGY

When the earth is irradiated by the sun, the ground absorbs some of this radiation. This heated ground warms the air above. Hot air rises in what are called "convection currents." The uneven heating of the earth's surface causes winds. For example, if the sun's rays hit land and water bodies (such as seas and oceans), the land heats up more quickly than water. This results in the air above the land moves upward more quickly than that over the water (hot air rises). As a result, the colder air over the water will rush in to fill the gap left by the rising air. This process gives rise to high- and low-pressure areas and thus to winds.

Wind energy is a non-polluting source of energy and is freely available in many areas. Wind turbines are becoming more efficient, making the cost of the electricity generation fall. Large balancing areas and aggregation benefits of large areas help to reduce the variability and forecast errors of wind power, as well as in pooling more cost-effective balancing resources (Holttinen *et al.*, 2011). There are already several power systems and control areas coping with large amounts of wind power (Soder *et al.*, 2007). Denmark, Germany, Spain, Portugal, and Ireland have integrated 9%–20% of wind energy (of yearly electricity demand). However, the disadvantages of wind energy exist as well. To be efficient, wind turbines need to be linked together in wind farms (often with 20 turbines or more). This looks unsightly and can be noisy. The wind farms also need to be sited reasonably close to populations so that the

electricity generated can be distributed easily and efficiently. Another disadvantage is that winds are intermittent and do not blow all the time. In this thesis, one turbine used to convert wind energy is optimized in order to improve the output power.

6.3 TYPES OF WIND TURBINES

There are many concepts to classify the types of wind turbines that are used. All of the wind turbines fall into two types depending on whether the turbine blade rotates about a horizontal axis or a vertical axis as shown in Fig. 6.3.

6.3.1 The horizontal axis wind turbine (HAWTs)

Horizontal axis wind turbines (HAWTs) are the common configuration that most of us think of when we think of a wind turbine. A HAWT has a similar design to a windmill. It has blades that look like a propeller that spins around the horizontal axis.

Horizontal axis wind turbines have the main rotor shaft and the electrical generator at the top of a tower, and they must be pointed toward the wind direction. Small turbines are pointed by a simple wind vane squarely placed with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind direction. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds.

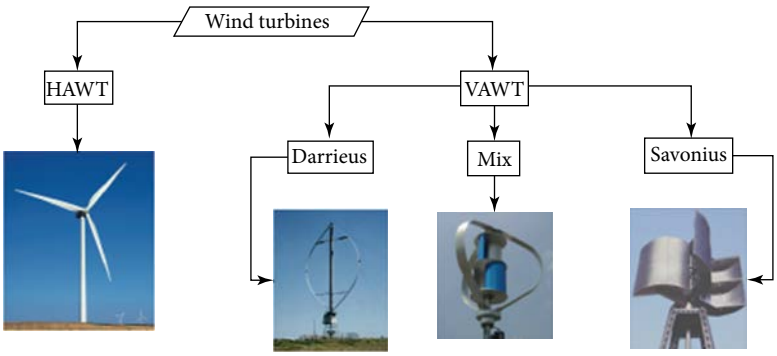

FIG. 6.3
Wind turbine configurations.

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Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a little.

Downwind machines have been built, despite the problem of turbulence, because they do not need an additional mechanism for keeping them in line with the wind. Additionally, in high winds, the blades can be allowed to bend, which reduces their swept area and thus their wind resistance. Since turbulence leads to fatigue failures and reliability is so important, most HAWTs are upwind machines.

The horizontal axis wind turbine (HAWT) is the favored form of turbines used for electricity generation purposes with a low solidity ratio (ratio of the blade area to the swept area) and a high tip speed ratio. This type of turbines has a high efficiency or power coefficient but a relatively low torque. By contrast, the traditional "American Windmill" or "Southern Cross," used throughout Australia and the USA for water pumping purposes, is a high solidity, low tip speed ratio device that produces a high torque suitable for direct drive of relatively simple mechanical pump systems. The HAWTs have a maximum theoretical power coefficient of approximately 0.59. However, in reality, this wind turbine can only achieve an average power coefficient of approximately of 0.3 (Qasim *et al.*, 2011). Figure 6.3 shows the main components of modem propeller type HAWTs. The main advantage of this machine is its high-power coefficient compared to other types. Nevertheless, the disadvantages of HAWTs include their operation at high starting wind velocity, low starting torque, the requirement of a yaw mechanism to turn the rotor toward the wind and the power loss when the rotors are tracking the wind directions. These are the main problems of the HAWTs, which are difficult to solve (Dang, 2009; and Roh and Kang, 2013).

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6.3.1.1 HAWT advantages

- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every 10 m up the wind speed can increase by 20% and the power output by 34%.
- High efficiency since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

6.3.1.2 HAWT disadvantages

- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of a horizontal axis wind turbine (gearbox, rotor shaft, and brake assembly) are being lifted into position.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).

- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
- HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning to avoid destroying or damaging itself.
- Cyclic stresses and vibration: When the turbine turns to face the wind, the rotating blades act like a gyroscope. As it pivots, gyroscopic precession tries to twist the turbine into a forward or backward somersault. For each blade on a wind generator's turbine, force is at a minimum when the blade is horizontal and at a maximum when the blade is vertical. This cyclic twisting can quickly fatigue and crack the blade roots, hub, and axle, of the turbines.

6.3.2 Vertical axis wind turbine (VAWTs)

The second major groups of wind turbine types are the vertical axis wind turbines (VAWTs). Vertical axis wind turbines (VAWTs) have the main rotor shaft arranged vertically (Aslam Bhutta *et al.*, 2012; and Mohan Kumar *et al.*, 2019).

A wide variety of VAWT configurations have been proposed, dating from the Persian VAWTs used for milling grain over thousands of years ago through to the Darrieus turbine, invented in 1926 by Georges Darrieus, which has been used extensively for power generation. One of the largest turbines ever built was the 96 m high 64 m diameter Éole Darrieus built in Canada, with a rated power output of 3.8 MW and a rotor weighing 100 tons. Other VAWT configurations include the Savonius VAWT, which is popular because of the simplicity of manufacture as well as the straight-bladed VAWTs. The straight-bladed VAWT includes the Musgrove turbine, which led to the successful testing of a 500 kW device at Carmarthen Bay, UK (Peace, 2004).

There are many variants of the vertical axial Darrieus and Savonius turbine design as well as a number of other similar devices under development (Fig. 6.3). The propeller type turbine is most commonly used in large-scale applications constituting nearly all of the turbines in the global market, while the vertical axis turbines are more commonly implemented in highway medium and small-scale installations. This type of wind turbines is the main focus of this research, whereby the rotor of the wind turbine rotates perpendicular to the direction of the wind.

Although VAWTs can capture ground-level winds, just like any turbine installed on a short tower, ground-level winds are subjected to friction. This slows wind down as it sweeps across the land. Both friction drag and turbulence in lower-level winds around buildings and trees decrease the power available to a turbine mounted at a ground level, resulting in very little extractable energy in them. The lower the wind speed, the less electricity a turbine will produce.

6.3.2.1 Traditional VAWT advantages

- They can rotate and hence produce electricity in any wind direction.
- Strong supporting tower is not needed because generator, gearbox, and other components are placed on the ground.

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- Low production cost as compared to horizontal axis wind turbines.
- As there is no need of pointing turbine in the wind direction to be efficient, yaw drive and pitch mechanism are not needed.
- Easy installation as compared to horizontal axis wind turbines.
- Easy to transport from one place to another.
- Low maintenance costs.
- They can be installed in urban areas.
- Low risk for human and birds because blades move at relatively low speeds.
- They are particularly suitable for areas with extreme weather conditions, such as in the mountains where they can supply electricity to mountain huts.

6.3.2.2 Traditional VAWT disadvantages

- As only one blade of the wind turbine works at a time, efficiency is very low compared to HAWTS.
- They need an initial push to start; this initial push that makes the blades to start spinning on their own must be started by a small motor.
- When compared to horizontal axis wind turbines, they are much less efficient because of the additional drag created when their blades rotate.
- They have relatively high vibration because the air flow near the ground creates turbulent flow.
- Because of vibration, bearing wear increases, which results in the increase of maintenance costs.
- They can create noise pollution.
- VAWTs may need guy wires to hold it up (guy wires are impractical and heavy in farm areas).

FIG. 6.4
Vertical axis resistance type windmill of the Sistan Basin in the border region of Iran and Afghanistan (Müller *et al.*, 2009).

The Sistan vertical axis windmill was one of the earliest wind turbines that was used in areas of Sistan and Khorasan of modern Iran (Mahdavinejad *et al.*, 2012). Those windmills were of the vertical axis type, with long vertical blades. They were used to grind corn and pump water (Hills, 1996). The Sistan wind turbine is a drag force driven turbine. These turbines are of special interest due to their inherent ease of building integration.

Müller *et al.* (2009) analyzed the oldest known form of wind energy converter, the Sistan type windmill shown in Fig. 6.4, and discussed modern adaptations of this drag force type energy converter for building integration. They found that this design improvement can lead to an increase of the theoretical

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efficiency of a drag force type rotor to about 48% (conservative) or 61% (optimistic) and that efficiencies higher than 40% can be achieved. These turbines are of special interest due to their inherent ease of building integration. They suggested improvements in the traditional turbine designs by adding disks at top and bottom of the rotor, which can improve efficiency to as high as 30%. Moreover, it is suggested that an increase in the turbine blades from 4 to 6 can have a further increase in the efficiency of 6%–7%. As it is a drag type wind turbine, the ability to self-start is inherently present. According to Müller *et al.* (2009), simple construction, solid view, and good efficiency make Sistan type wind mill a real building integrated wind turbine. However, more research is required in the field to correctly identify the optimum configurations for the turbine.

6.4 INTRODUCTION TO THE WIND ENERGY

6.4.1 Properties of the wind

In order to discuss wind energy and specifically on the reasons often given for and against vertical axis wind energy capture, a preliminary discussion of the wind itself is necessary.

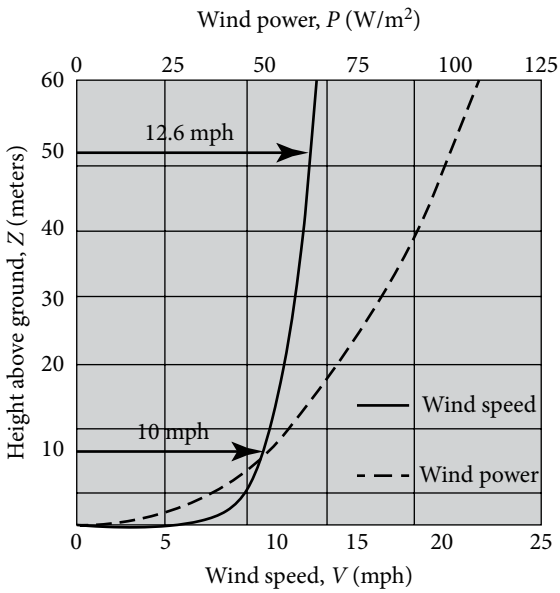

FIG. 6.5
The wind power and the speed profile with height (Blackwood, 2016; and NREL, 2021).

Certain characteristics of the wind are shared with the atmosphere and are accordingly deemed as "common knowledge" to humans who occupy the lower atmosphere. It is well known that air density decreases with height and air temperature decreases with increasing altitude. Less widely recognized or possibly less commonly considered are three additional wind characteristics that are very important for wind energy capture, namely, (i) wind speed increases with height due to reduced contact with the earth's surface and the resulting reduced friction, (ii) small-scale (local) turbulence decreases with height, a feature commonly stated by pilots as "the air smooths out with altitude," and (iii) the power in the wind increases with height due to the previous two conditions, as provided by the National Renewable Energy Laboratory (NREL) and shown in Fig. 6.5.

6.4.2 Wind speed and power variation with elevation

To calculate the wind speed at the height of the hub, it must be noticed that wind speed varies with height

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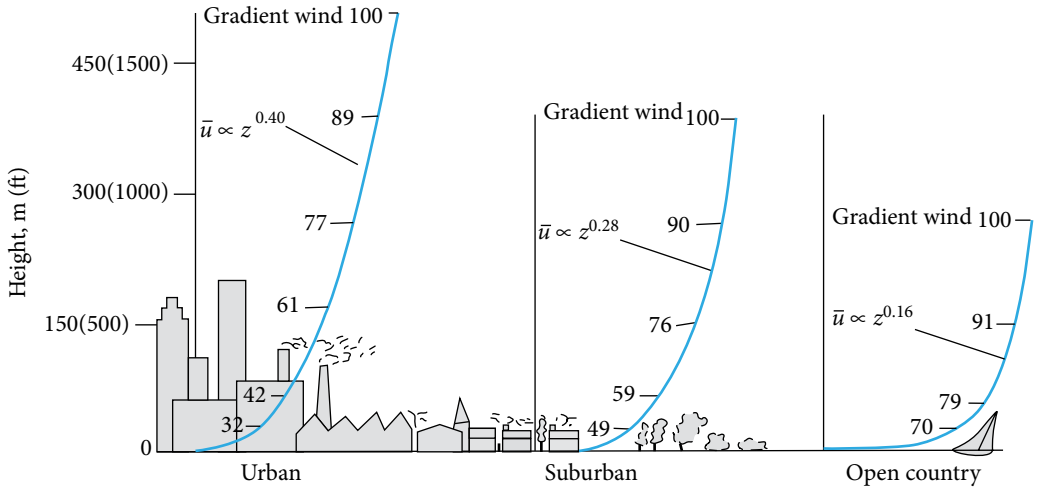

FIG. 6.6
Mean velocity profiles for various types of environments.

due to the friction against the structure of the ground, which slows the wind. This phenomenon is called wind gradient or wind profile (Johnson, 1999; and Safari and Gasore, 2010).

If a height "z" is considered, the average of the wind speed at this height is described by Eq. (6.1),

$$V_h = V_{Zo}\left(\frac{h}{Z_o}\right)^{\alpha}, \tag{6.1}$$

where Z_o is the reference height, V_{zo} is the wind speed at reference height Z_o, and α is the value depending on the roughness class of the terrain as shown in Fig. 6.6.

The terrain index, α, is not constant. Rather, it varies with terrain type, ground cover, wind direction, density of built environment, and atmospheric conditions. Wind velocity increases with the power of the structural height.

6.5 INTRODUCTION TO WIND TURBINE TECHNOLOGY

The performance characteristics of a wind turbine are generally measured numbers, which are holistic to the system and represent an overall specification for the machine rather than attributed to a specific component in the system. These characteristics are empirical in nature and are the result of the combination of the aerodynamic, mechanical, and electrical characteristics of the individual components (Balat, 2009).

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6.5.1 Advance ratio or tip speed ratio (TSR, λ)

The blade tip speed ratio (λ) will be used in the present analysis to obtain the optimum operating conditions for the wind turbine. It is defined as the ratio of circumferential velocity of the turbine to the wind velocity as calculated in Eq. (6.2). The advance ratio is often used to classify wind energy capture systems and to compare turbines and types of turbines. Turbines achieving advance ratios (greater than 1) are considered to be lift dominated devices, as they are moving faster than the wind. Turbines with advance ratios (less than 1) are commonly called "drag" devices, meaning that their propulsion is dominated by wind impact forces on the blades. Higher tip speeds are generally desirable for the generation of electricity, while lower tip speeds are usually found on high torque turbines, which are used for direct mechanical work (e.g., pumping water and compressing air),

$$TSR\ (\lambda) = \frac{\omega R}{V} = \frac{2\pi NR}{60V}, \tag{6.2}$$

where R is the radius of the turbine rotor, N is the number of rotations, and V is the wind speed.

The tip speed ratio at the maximum power coefficient is usually determined according to the turbine type.

If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the openings between the blades with little power extraction. On the other hand, if the rotor turns too fast, the rotating blades will act like a wall and hence, it will obstruct the wind flow, again reducing power extraction. Wind turbines must thus be designed to operate at their optimal wind tip speed ratio in order to extract as much power as possible from the wind stream. Wind tip ratios depend on the particular wind turbine design used, the rotor airfoil profile used, as well as the number of blades used.

6.5.2 Power coefficient (*Cp*)

Wind turbines cannot extract the power in a wind stream completely. When the wind stream passes through the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as the power coefficient (*Cp*). Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind (Hansen, 2015). Mathematically, the theoretical power is calculated in Eq. (6.3),

$$W_{WIND} = \frac{\rho A V^3}{2}, \tag{6.3}$$

where ρ is the air density and A is the swept area of the turbine.

The power coefficient also known as the coefficient of performance in some circles for a turbine is generally given as the ratio of the power generated by the machine to the power available in the wind

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at the point of extraction. *Cp* is an empirically measured characteristic of the turbine and is used in the form shown in Eq. (6.4) for predicting power production at a given wind speed,

$$Cp = \frac{W_{gen}}{0.5\rho A V^3}, \tag{6.4}$$

where W_{gen} is the power produced by the generator of turbine.

6.5.3 The starting wind speed and the cut-in wind speed

The starting wind speed is the minimum wind speed for the wind turbine to start rotating from stationary to continuous movement. The cut-in wind speed is the minimum wind speed for the wind turbine to start producing power. Because the wind turbine is designed to generate electricity, the cut-in wind speed is more important. In general, the cut-in speed of a small wind turbine is in the range of 3–6 (m/s).

The kinetic energy of wind is proportional to the cube of the wind speed. Hence, in the very low wind speed, the energy conversion of wind is very low.

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6.5.4 Basic theory of wind turbines

The output power from a turbine rotor called also mechanical power (W_m) and the wind kinetic energy per unit time, W_{wind}, are given by Eq. (6.5),

$$Wm = T \cdot \omega. \tag{6.5}$$

The theoretical power generated ($W_{gen.}$) by the impeller type wind turbine is calculated by the following equation:

$$W_{gen.} = \left(\frac{T_{avr} V}{r}\right)\eta, \tag{6.6}$$

where T_{avr} is the average torque and η is the wind turbine efficiency, which in turns depends on the following factors and is calculated as

$$\eta = Cp * C * N_g * N_b, \tag{6.7}$$

where $C = C_l$ or $= C_D$ (or resultant of them)—are lift and drag factors, respectively, and depend on the shape and form of the blades or vanes and on the orientation of the wind flow with respect to the object, N_g is generator efficiency 80% or possibly more for a permanent magnet generator or a grid-connected induction generator, and N_b is gearbox/bearing efficiency 95%.

The main objective is to maximize the coefficient *C*. In general, drag factor C_D is a function of the turbine element geometry and the Reynolds number. For a propeller wind turbine, A_s is the swept

area of rotating blades, but the actual area of blades is four to five times less than the swept area (Qasim *et al.*, 2011). The wind between propellers passes freely and does not affect the blades. Therefore, the real output power of the propeller wind turbine is less than the theoretical power of the turbine.

6.6 MODERN VERTICAL AXIS WIND TURBINE TYPES

As stated earlier, there are a few problems inherent to the current turbine designs, including low starting torque, blade lift forces, low efficiency, poor building integration, and many others. In the past few decades, engineers have come up with many new and innovative design approaches to resolve these issues.

6.6.1 Theoretical aerodynamic

Wind turbine generators use mainly aerodynamic lift and drag forces acting on their surfaces of blades or vanes. Today, many researchers state that horizontal axis wind turbines (lift force design) theoretically have higher power efficiencies than the vertical axis one (drag force design) (Nobile *et al.*, 2011). There are also researchers who state that under turbulent conditions with rapid changes in the wind direction, vertical turbines practically generate more electricity despite their lower efficiency.

6.6.2 Lift force wind turbine

The theoretical maximum power efficiency of any design of a wind turbine operating in open atmosphere is lower than 59.3% efficiency (Mathew, 2006). This is known as the Betz limit. It is obtained by setting up the ratio between the maximum powers extractable and the energy in the wind as it passes the actuator disc.

The common value is around 0.35–0.45 even in the best designed wind turbines. Apart from this one, there are other energy losses in a complete wind turbine system (the generator, bearings, power transmission, etc.). Therefore, only 10%–30% of the power of the wind is ever actually converted into usable electricity.

6.6.2.1 Energy capture using the lift principle

Consider a wind turbine that intercepts the flow of air moving with velocity V_2. The different quantities involved in the physics of the moving air are the pressure (p), the velocity (V), the cross-sectional area (A) at different locations along the stream lines, and the thrust on the blades of wind turbine (T). The upstream condition is identified with a subscript of 2, the downstream condition is identified with a subscript of 1, and the turbine locations are identified by subscripts of T.

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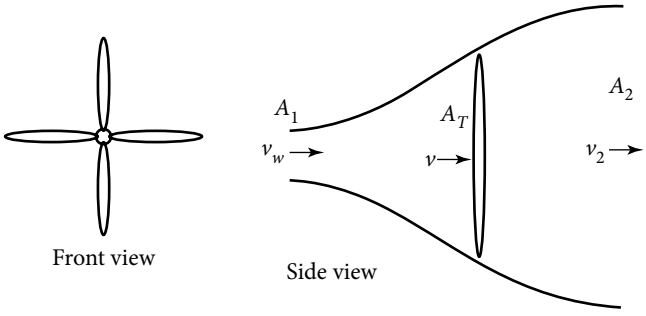

FIG. 6.7
Profile of a wind turbine illustrating the path of the airflow (Rezaeiha *et al.*, 2018).

We then consider Fig. 6.7.

Since the air is incompressible, the mass flow rate of air (kg/s), $\dot{m}$, can be defined as

$$\dot{m} = \rho A_1 V w = \rho A_T V = \rho A_2 V_2, \tag{6.8}$$

where ρ is the density of air (kg/m^3), A_1 is the cross-sectional area of the wind approaching the turbine, A_2 is the cross-sectional area of the air stream after the turbine, A_T is the area of the turbine, V_w is the upstream wind speed, V is the air velocity at the turbine blades, and V_2 is the velocity of the downstream air after it passes the turbine. The cross-sectional areas are in units of m^2 and the air speed (velocity) in m/s.

The rate at which kinetic energy is extracted from the wind is

$$P = \dot{m}\frac{1}{2}\left(V_w^2 - V_2^2\right). \tag{6.9}$$

The rate at which kinetic energy is extracted from the turbine rotor is

$$P_T = \dot{m}V(V_w - V_2). \tag{6.10}$$

Using the mass balance relationship at the turbine from Eq. (6.8) and substituting it into Eqs. (6.9) and (6.10) results in

$$P = \dot{m}\frac{1}{2}\left(V_w^2 - V_2^2\right) = \rho A_T V \frac{1}{2}\left(V_w^2 - V_2^2\right), \tag{6.11}$$

$$P_T = \dot{m}V\left(V_w - V_2\right) = \rho A_T V^2\left(V_w - V_2\right). \tag{6.12}$$

From physics, we apply the law of conservation of energy and state that $P_T = P$, thereby setting Eq. (6.11) and equalizing to each other. This results in the following relationship:

$$\rho A_T V \frac{1}{2}\left(V_w^2 - V_2^2\right) = \rho A_T V^2\left(V_w - V_2\right),$$

which can be further reduced to

$$\frac{1}{2}\left(V_w - V_2\right)\left(V_w + V_2\right) = V\left(V_w - V_2\right),$$

$$\frac{1}{2}\left(V_w + V_2\right) = V. \tag{6.13}$$

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This simply states that the airspeed at the turbine is the average of the airspeeds upstream and downstream from the turbine. Using this relationship, we can now restate the power extracted from the wind at the turbine, Eq. (6.11), as

$$P = P_T = \rho A_T V \frac{1}{2}\left(V_w^2 - V_2^2\right) = \frac{1}{4}\rho A_T \left(V_w^3 - V_w V_2^2 + V_w^2 V_2 - V_2^3\right). \tag{6.14}$$

By factoring out the wind speed term, Eq. (6.14) can be restated as

$$P_T = \frac{1}{4}\rho A_T V_w^3 \left[1 - \left(\frac{V_2}{V_w}\right)^2 + \left(\frac{V_2}{V_w}\right) - \left(\frac{V_2}{V_w}\right)^3\right]. \tag{6.15}$$

To simplify the equation, let us define the following term:

$$\alpha = \frac{V_2}{V_w}. \tag{6.16}$$

Using this relationship, Eq. (6.15) becomes

$$P_T = 1/4\rho A_T V_w^3 (1 - a^2 + a - a^3). \tag{6.17}$$

The results of Eq. (6.17) show that the power extracted by the turbine is a function of the ratio of the downstream and upstream air velocities, $\frac{V_2}{V_w}$, and proportional to the cube of the upstream wind (V_w^3).

Consider the total rate of kinetic energy from the wind, P_{total}, passing through an equivalent area in the absence of a turbine. Determining this relationship will be key in determining the maximum efficiency of our ideal wind turbine.

From physics, we know that power is defined as the incremental change in work over time, where work is equivalent to the kinetic energy of the wind. The kinetic energy of the wind is defined as

$$E = \frac{1}{2}mV^2.$$

The power can be calculated as

$$P = \frac{dE}{dt} = \frac{d}{dt}\left(\frac{1}{2}mV^2\right). \tag{6.18}$$

Using the chain rule and Eq. (6.18), we have

$$P = \frac{1}{2}\frac{d}{dt}(mV^2) = \frac{1}{2}\left(2mV\frac{dV}{dt} + V^2\frac{dm}{dt}\right). \tag{6.19}$$

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In the absence of the turbine, the wind velocity, V_w, is constant; therefore, the $\frac{dV}{dt}$ term goes to zero. Using the results from Eqs (6.8) and (6.19) and remembering that the cross-sectional areas, A_1, A_T, A_2, in this case, are equivalent, the total power, P_{total}, can now be expressed as

$$P_{total} = \frac{1}{2}V_w^2\frac{dm}{dt} = \frac{1}{2}V_w^2\dot{m} = \frac{1}{2}\rho A_T V_w^3. \tag{6.20}$$

Similar to the results found for the extractable turbine, the total power of the wind is proportional to the cube of the wind velocity.

Now that we have expressions for the power extracted at the turbine (P_T) and the total power available from the wind (P_{total}), we can now create an expression for the efficiency of the ideal wind turbine, $\eta = \frac{P_T}{P_{total}}$. Using the results from Eqs (6.17) and (6.20), the efficiency factor is

$$\eta = \frac{P_T}{P_{total}} = \frac{\frac{1}{4}\rho A_T V_w^3\left(1 - a^2 + a - a^3\right)}{\frac{1}{2}\rho A_T V_w^3} = \frac{1}{2}\left(1 - a^2 + a - a^3\right). \tag{6.21}$$

To determine the maximum possible efficiency, we will use calculus to take the derivative of Eq. (6.15) with respect to a, set it equal to zero, and solve for a,

$$d\eta/da = \frac{1d}{2da}\left(1 - a^2 + a - a^3\right) = \frac{1}{2}\left(-2a + 1 - 3a^2\right) = \frac{1}{2}(1 + a)(1 - 3a).$$

By inserting the relationship for a from (6.16), we can state this in terms of the upstream and downstream velocities as

$$0 = \frac{1}{2}(1 + a)(1 - 3a) = \frac{1}{2}\left(1 + \frac{V_2}{V_w}\right)\left(1 - 3\frac{V_2}{V_w}\right). \tag{6.22}$$

This equation results in two solutions. The first solution,

$$0 = \left(1 + \frac{V_2}{V_w}\right), \quad \Rightarrow V_w = -V_2,$$

does not appear to be valid in a practical sense since the downstream airspeed cannot be in the opposite direction of the upstream wind.

The second solution results in

$$0 = \left(1 - 3\frac{V_2}{V_w}\right) \Rightarrow 3V_2 = V_w \Rightarrow V_2 = \frac{1}{3}V_w. \tag{6.23}$$

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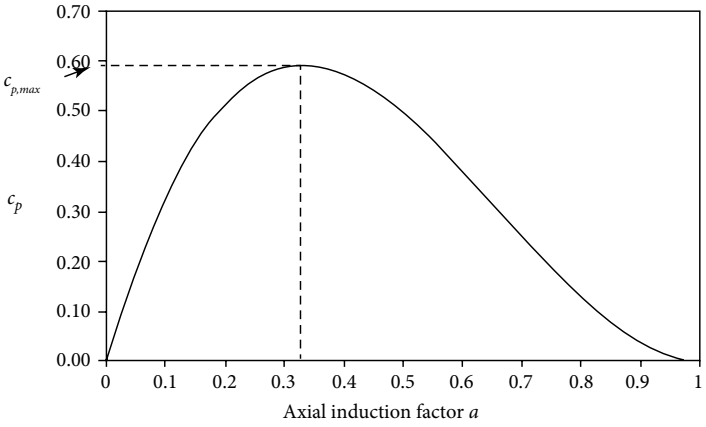

FIG. 6.8
Power coefficient as a function of axial induction factor a (Blackwell *et al.*, 1976).

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This solution is more practical and significant in that it shows that in order to maximize the power from the turbine, the downstream airspeed must be equal to one-third of the upstream wind.

To determine the maximum efficiency factor numerically, we must take results from Eq. (6.23) and insert them into Eq. (6.21). From Eq. (6.23), we can calculate the value of a,

$$a = \frac{V_2}{V_w} = \frac{1}{3}.$$

This results in Eq. (6.22) becoming

$$\eta = \frac{1}{2}\left(1 - \frac{1}{9} + \frac{1}{3} - \frac{1}{27}\right) = \frac{16}{27} = 59.26\%. \tag{6.24}$$

This is referred to as the Betz limit and was first introduced by the German engineer Albert Betz in 1919.

This indicates that the power coefficient is only a function of the axial induction factor (a). It is easy to derive that the maximum power coefficient reaches its maximum value of 16/27 when $a = 1/3$ (Fig. 6.8).

6.7 DRAG FORCE WIND TURBINE

The simplest turbine would use the drag force and would consist of flat or curved plates, cups, discs, or similar shapes attached to a vertical or horizontal shaft perpendicular to the flow, utilizing the

difference between drag forces on the plate pushed by the wind and on the plate advancing against the wind. The oldest documented windmills were typical drag force machines that had shields (Persian type) or plate rotating devices (Chinese type) to decrease the drag force on the half of the rotor that advances against the wind.

6.7.1 Energy capture using the drag principle

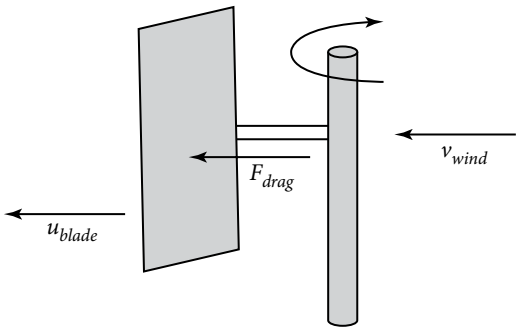

FIG. 6.9
Simplified model of the (drag-only) VAWT (Gosselin, 2015).

Wind energy devices powered solely by drag forces are able to capture the wind with significantly less efficiency than the theoretical maximum derived earlier in this chapter. Calculation of the maximum power coefficient obtainable by a device propelled by only drag forces on a vertical axis blade has been derived by (Manwell *et al.*, 2010) and is shown in Fig. 6.9 as well for the purpose of completeness.

Starting with a "drag-only" VAWT that is modeled as a single blade rotating about a vertical shaft, as shown in Fig. 6.9, and subjecting it to an undisturbed airstream of velocity V_{wind}, an equation for the drag force on the blade F_D can be written from Kaltschmitt *et al.* (2007). The drag force on the blade follows from the equation

$$F_D = C_D \frac{1}{2}\rho A\left(V_{wind} - u_{blade}\right)^2, \tag{6.25}$$

where $(V_{wind} - u_{blade})$ is the velocity relative to the blade.

This equation of drag force can be related to power based on the coefficient of drag, as given by

$$\begin{aligned}\text{Power (W)} &= F_D \times u_{blade}\\ &= C_D \frac{1}{2}\rho A\left(V_{wind} - u_{blade}\right)^2 u_{blade}\\ &= C_D \frac{1}{2}\rho A\left(uV_{wind}^2 - 2V_{wind}u^2 + {u_{blade}}^3\right)\\ &= C_D \times \frac{1}{2}\rho \times A \times V_{wind}^3\left(\frac{u_{blade}}{V_{wind}} - 2\frac{u_{blade}^2}{V_{wind}^2} + \frac{u_{blade}^3}{V_{wind}^3}\right),\end{aligned} \tag{6.26}$$

Let $\lambda = \dfrac{u_{blade}}{V_{wind}}$,

$$\text{Power (W)} = C_D \times \frac{1}{2}\rho \times A \times V_{wind}^3\left(\lambda - 2\lambda^2 + \lambda^3\right).$$

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Thus, turbine power is proportional to the cube of wind's speed, air density, and the swept area of the rotor wind turbine. Hence, the speed of wind contributes to the increase of power more than any other parameters,

$$Cp = \frac{\text{turbine power output}}{\text{wind power}},$$

$$Cp = \frac{C_D\left(V_{wind} - u_{blade}\right)^2 u_{blade}}{V_{wind}^3},$$

$$Cp = C_D\left(\lambda - 2\lambda^2 + \lambda^3\right). \tag{6.27}$$

Power extraction is maximum if $\frac{dCp}{d\lambda} = 0 = C_D(1-4\lambda+3\lambda^2)$,

$(1-4\lambda+3\lambda^2) = 0.$

After simplification, we get

$$\lambda = 1/3. \tag{6.28}$$

In drag turbine, the rotor cannot rotate with more than wind velocity. Thus, one can conclude that the maximum power is given by

$$Cp_{Max} = \frac{4}{27}C_D. \tag{6.29}$$

The turbine power depends on the speed of wind; therefore, it is favorable to deploy wind turbines at high altitudes in order to increase power output. This is because the speed of wind increases with height above ground level, and this implies building high towers for the turbine.

6.8 SIMILARITY BETWEEN MODEL AND PROTOTYPE OF THE VANE TYPE WIND TURBINE

There are three necessary conditions for complete similarity between a model and prototype. The first condition is geometric similarity—the model must be the same shape as the prototype but may be scaled by some constant scale factor. The second condition is kinematic similarity, which means that the velocity at any point in the model flow must be proportional (by a constant scale factor) to the velocity at the corresponding point in the prototype flow. The third and the most restrictive similarity condition is that of dynamic similarity. Dynamic similarity is achieved when all forces in the model flow scale by a constant factor to corresponding forces in the prototype flow (force scale equivalence) (Mathew, 2006; and Nobile *et al.*, 2011).

Wind turbines come in different sizes. Wind turbines will experience a wide range of variables when it operates. These variables complicate the process of comparison of different sizes of turbines in terms

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of their performance. To deal with this, the help of dimensional analysis is taken. One of the qualities of dimensional analysis is that geometrically similar turbines will produce the same non-dimensional results. This allows one to make a comparison between different size wind turbines in terms of power output and other related variables.

There are six parameters that are relevant to the wind turbines. They are

$$W,\ V,\ \rho,\ D,\ \mu,\ N,$$

where W is the power delivered to the grid, V is the wind speed, ρ is the wind density, μ is the wind dynamic viscosity, and N is the rotational speed of the rotor. The units of power are energy per time or $[W] = \text{kg m}^2\ \text{s}^{-3}$. The other units are $[\rho] = \text{kg m}^{-3}$, $[V] = \text{m s}^{-1}$, and $[D] = \text{m}$. Therefore, the unit system for this problem contains three dimensions,

$$\text{Kg, m, s} = m,\ L,\ T.$$

Therefore, then, $6 - 3 = 3$.

We will have 3 Π, the dimensionless product as a function of the other,

$$\Pi = \Phi\left(\Pi 0,\ \Pi 1,\ \Pi 2\right).$$

Π by definition is unitless; therefore, $[\Pi] = m^0\ L^0\ T^0$. Also, since we are after the power W, let us lump W into Π and find out what combination of the other variables we need to make it dimensionless,

$$\Pi_0 = W,\ \rho,\ D,\ V.$$

Plugging in the relevant units, we have

$$m^0 L^0 T^0 = m\ L^2 T^{-3} (m\ L^{-3})^a (L)^b (LT^{-1})^c,$$
$$m^0 L^0 T^0 = m^{1+a} L^{2-3a+b+c}\ T^{-3-c}.$$

Since Π_0 is dimensionless,

$$1 + a = 0,$$
$$2 - 3a + b + c = 0,$$
$$-3 - c = 0.$$

These equations have the solution $a = -1$, $b = -2$, $c = -3$ so that

$$\Pi_0 = W\rho^{-1} D^{-2} V^{-3},$$
$$\Pi_0 = \frac{W}{\rho D^2 V^3} = Cp,$$
$$\Pi_1 = \mu,\ \rho,\ D,\ V.$$

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Plugging in the relevant units, we have

$$m^0 L^0 T^0 = m\ L^{-1}T^{-1}(m\ L^{-3})^a (L)^b (L\ T^{-1})^c,$$
$$m^0 L^0 T^0 = m^{1+a} L^{-1-3a+b+c} T^{-1-c}.$$

Since Π_1 is dimensionless,

$$1 + a = 0,$$
$$-1 - 3a + b + c = 0,$$
$$-1 - c = 0.$$

These equations have the solution $a = -1$, $b = -1$, $c = -1$ so that

$$\Pi_1 = \mu\rho^{-1}D^{-1}V^{-1},$$
$$\Pi_1 = \frac{\mu}{\rho DV} = \frac{1}{Re},$$
$$\Pi_2 = N,\ \rho,\ D,\ V.$$

Plugging in the relevant units, we have

$$m^0 L^0 T^0 = T^{-1}\left(m\ L^{-3}\right)^a \left(L\right)^b \left(L\ T^{-1}\right)^c,$$
$$m^0 L^0 T^0 = m^{0-a} L^{0-3a+b+c} T^{-1-c}.$$

Since Π_2 is dimensionless,

$$0 - a = 0,$$
$$-3a + b + c = 0,$$
$$-1 - c = 0.$$

These equations have the solution $a = 0$, $b = 1$, $c = -1$ so that

$$\Pi_2 = N\rho^0 D^1 V^{-1},$$
$$\Pi_2 = \frac{ND}{V} = \lambda.$$

And, just as before with the physics, we have

$$\frac{W}{\rho D^2 V^3} = Cp = f\left(Re,\ \lambda\right). \tag{6.30}$$

The swept areas, heights, and diameters of the rotors vary. Torque and speed of the rotors will vary as the proportions of the rotor are changed. As the area of the rotor is increased, the amount of power generated will also increase. However, it should be noted (for wind speed V constant) that if the diameter of the rotor is increased, the torque will increase and the speed of rotor will decrease. The

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power coefficient is the most important variable in wind turbine aerodynamics; it represents the amount of energy in a specific turbine that can absorb from the wind. The speed at the tip of the blade is written as the product of the blade radius and the rotational speed of the blade ($U = \omega * r$) and $\omega = \pi\, DN$, where ω is the angular velocity of the turbine blade, D is the diameter of the turbine blade, and N is the speed of the blade/wheel (or the rotational speed of the rotor).

This variable is nondimensionalized by the wind speed to get the tip speed ratio. Therefore, the only appropriate comparisons of the rotors can be made on the basis of the power coefficient and tip speed ratios.

6.9 CONCLUSION

Wind energy is a source of renewable energy that comes from the air flowing through the earth's surface. Wind energy is defined as a form of energy in which turbines convert the kinetic energy of the wind into mechanical or electrical energy. Wind energy is considered one of the pioneers of a technological boom that may lead to an increase in the efficiency of energy production, and its future seems promising, as the kinetic energy of the wind is used to create mechanical energy and the generators convert this energy into electricity so that it can be used for the benefit of humanity. There are many people who rely on windmills, which represent an innovative and creative technical skill that relies on wind because wind energy is clean and renewable to no end.

Wind energy is one of the fastest growing sources of new electricity generation in the world, and these growth trends can be linked to multiple benefits, including the following: Green energy: The electric energy produced from wind energy is clean, which means that it does not produce any pollution or gases. Economic development: In addition to wind energy as a low-cost energy, wind energy is a source of electricity that is produced locally and does not require fuel, which enables local communities to preserve money in their economy.

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CHAPTER

7 BIOMASS ENERGY: CLEAN FUELS FOR DOMESTIC USE AND INSTITUTIONAL FRAMEWORK IN AFRICA

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7.1 INTRODUCTION

In general terms, biomass energy refers to the energy that is generated from living things, plants and animals. It is also described as a kind of renewable energy from plants and animals (U.S. Energy Information Administration, 2020b). Biomass is momentarily portrayed as organic matter sustainable over time, which can be utilized as an environmentally friendly power asset, either straightforwardly by ignition to create heat or by implication, after a change into different types of semi-handled bioenergy (like wood pellets or ethanol). Wood remains the main kind of biomass that characterizes 87% of the absolute biomass energy, either collected and utilized as fuel or gotten from wood items. It principally comprises carbs and lignin delivered by the photosynthetic interaction, and it may be straightforwardly utilized in current energy applications, for example, creating power, fluid powers, and making bio-synthetic compounds (Foster *et al.*, 2007; Wicke *et al.*, 2011; Stecher *et al.*, 2013; and Petrie, 2014). The main sources of biomass are forestry and crops and residues, animal residuals, industrial residues, sewage, and solid waste, among others. The woody biomass potential for the most part has large amounts of stumps, tree limbs, residuals of sawmills, and sawdust.

There are many factors that drive the increasing need for renewable energy. Promoting access to clean household energy is critical in the pursuit of universal energy access by 2030, a target among the United

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Nation's Sustainable Development Goals. The majority of people in sub-Saharan Africa, approximately 76% of the region's population, depend on traditional biomass (i.e., crude energy sources) as their primary energy source (International Energy Agency, 2006). Use of traditional biomass leads to high household pollution, resulting in health hazards and is estimated to cause 1.6–3.6 million premature deaths (World Health Organization, 2018). Improved technologies have established energy-efficient mechanisms to access and use bioenergy. The United States Energy Information Agency (U.S. Energy Information Administration, 2008) estimated a rapid increment in the world energy demand until 2025, emphasizing that majority of this demand would spring from the emerging economies in Africa and Asia. However, to meet the world's energy demand, there would have to be an equivalent energy supply, and based on the available technology, energy sources, and cost constraints, there is the potential to rely on dirty energy sources instead of clean energy sources (Kamble *et al.*, 2019).

Notably, Kamble *et al.* (2019) further stated that there is no existing one source of energy that can meet the rapidly growing demand, which implies that there is a need for the combination of energy sources to meet the existing demand. The combination of energy sources includes the utilization of biomass energy, sourced from feedstock such as plants, microbial cells, agricultural, forestry, and municipal wastes and residues. Another suggested clean energy source is the co-gasification of coal and biomass as an emerging clean energy technology, which ensures relatively high thermodynamic efficiency with relatively low carbon emissions.

However, the choice of energy source should be carefully made to mitigate the negative effects of dirty energy sources' production and usage, which could be harmful to the ecosystem as well as the sustainability of the human race (Ihayere *et al.*, 2020; and Karakara and Osabuohien, 2021). For instance, the traditional biomass has been proven to negatively impact the health of the economy and lead to the loss of 600 000 lives (Lambe *et al.*, 2015). The impact has led to complications that have cost an economic burden of about 0.5% and 2.5% portions of the gross domestic product in the world—equivalently $150–$750 billion according to the IEA (International Energy Agency, 2019).

Furthermore, Africa is characterized by endemic low *per capita* energy creation and utilization. This is an outcome of Africa's poor financial presentation since the primary oil stun in the mid-1970s, especially, in oil-producing sub-Sahara African nations. Africa's energy creation is about 9.5% of the world's absolute yield, including 12.1% of the world's crude petroleum creation; 6.6% of flammable gas yield; 4.7% of the world's hard coal; and 3.1% of hydroelectric force. The mainland holds 9.7% of the world's demonstrated oil saves, including a huge segment of new disclosures. Africa is a huge net exporter of energy assets (475 million tons of oil comparable each year) identical to 40%–45% of the landmass' creation. However, the landmass of 930 million occupants burns through a minimal measure of energy *per capita*. Africa has recently 3.6% of the worldwide refining limit; it creates just 3.1% of the world's power and burns through just 9% of its absolute oil creation, sending out the rest. A lot of world energy utilization is just 3% contrasted with its 14% of the total populace (International Energy Agency, 2019).

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In many African countries, under-estimation of the need for energy partnerships to redesign advancements and fortify energy development activities has brought about a low degree of specialized productivity. At the creation level, obsolete, less-effective advancements mean less energy yield per unit of fuel information sources and more GHG emanation per unit energy yield. In the transportation and circulation stages, there is a high pace of unaccounted-for misfortunes. In addition, Nigeria has over 40.1% of the 433×10^6 poor across Africa and her poor face challenges of affordability (Schoch and Lakner, 2020). Even though Africans can afford the basic improved cooling solution, the problem of high-cost stands as obstacle for the poor population and affect the overall growth of the market (Bundschuh and Chen, 2014). However, recently with higher income, Bildirici and Ozaksoy (2017) noted about 81% of the population of Africa depend on biomass energy sources for economic purposes, household, and cooking activities. Its relevance has increased due to the use of agricultural and industrial by-products.

Therefore, the safe energy policy directive calls for the utilization of clean energy sources, and one way to ensure compliance is with the introduction of the institutional framework (Akinyemi *et al.*, 2019). An institutional framework for clean energy is also necessary as Karakara and Osabuohien (2021) noted that the majority of households, especially in sub-Saharan Africa, are deprived of clean energy sources for their domestic needs, further noting that most of the household domestic needs include cooking, lighting, and heating. Thus, this chapter sets out to examine the influence of the institutional framework for ensuring clean energy for domestic use. This is deemed necessary as the sustainable development goal seven (SDG_7) is concerned with ensuring access to affordable, reliable, modern, and sustainable energy for all and what is currently attainable in Africa, as noted by Egbetokun *et al.* (2018, 2020), is that the increase in the population and economic activities have led to the fast-degrading environment due to the dirty growth syndrome, weak environmental regulations, and non-existence of abatement measures.

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7.2 BIOMASS AND RENEWABLE ENERGY: CONTEXT MATTERS[1]

7.2.1 Biomass energy conceptualization and production

There are two classes of energy used in the household: solid fuels and non-solid fuels. The solid fuels include coal, peat, and solid biomass (wood, agricultural residues, and dung) (Emagbetere *et al.*, 2016). In simple terms, biomass energy is mostly referred to as the poor man's fuel, and it is influenced by different factors like climate, the use of land patterns, income distribution, cultural factors, and cooking techniques. Mehedintu *et al.* (2018) capture biomass as organic matters that exist in the biosphere and

[1] For the sake of simplicity and clarity, this chapter uses biomass, clean energy, and renewable energy almost interchangeably.

they arise from plant or animal origin and are obtained through natural or artificial transformation. Biomass extracts biofuels from firewood, wood, shavings, pellets, and some fruits stones such as olives, avocados, and nutshells.

The characteristics of biomass make it efficient for energy sources because through direct combustion it is burned in waste conversion plants and can produce electricity in boilers that produce heat at residential and industrial levels (Manzano, 2007). The relevance of biomass is fast increasing because many countries see it as an important fuel used in many countries, especially for cooking and heating. That is why households across the world depend on the traditional use of biomass, especially, in rural areas. Rural households generate biomass energy through the production and conversion of wood. This is considered an informal income approach to generating activity for domestic use (World Energy Outlook, 2013). This has led to an increase in the consumption of energy in developing countries and has surpassed the consumption in developing economies.

The conversion of biomass materials into energy for both domestic and non-domestic use can be carried out through different processes, which technically include direct combustion, thermochemical conversion, chemical conversion, and biological conversion (U.S. Energy Information Administration, 2020b). The direct combustion method is concerned with burning biomass materials to produce heat for industrial processes and electricity generation in steam turbines. For example, cutting and chopping firewood that is processed and burned directly in domestic appliances like stoves and boilers. The thermochemical conversion is concerned with the conversion that aims to produce solid, gaseous, and liquid fuels. The thermochemical conversion process utilizes pyrolysis, hydrotreating, and gasification, which uniquely comprises the use of pressurized vessels, termed gasifiers at high temperatures. Pyrolysis, hydroheating, and gasification differ based on the amount of heat and oxygen introduced, which result in different energy products. Notably, biomass pyrolysis produces charcoal, bio-oil, renewable diesel, methane, and hydrogen. Hydrotreating produces renewable diesel, renewable gasoline, and renewable jet fuel, while gasification hydrogen-rich synthesis gas, which can be used in diesel engines and gas turbines.

The chemical production of biomass energy is carried out using transesterification, which is necessary for the conversion of fats and greases into fatty acid methyl esters, which serve as an ingredient for the production of biodiesel. The biological production of biomass energy is concerned with the fermentation of biomass materials into ethanol and anaerobic digestion with a goal to produce renewable natural gases such as biogas and bio-methane. Notably, the anaerobic digestion process is carried out at sewage treatment plants as well as dairy and livestock operations.

7.2.2 Biomass and renewable energy policy and empirics

Concerning the existing policies for driving clean energy, every two years, EU countries report their progress toward the EU's 2020 renewable energy goals (European Commission, 2020a). The Commission noted that the declining cost of renewable energy technologies, innovation in

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relation to storage systems, electric vehicles, and digitalization are already driving greater energy system integration in Europe (European Commission, 2020b). This percolates the need to increase renewable energy sources. The original Renewable Energy Directive-RED (2009/28/EC) establishes an overall policy that requires the EU to fulfill at least 20% of its total energy needs with renewable energy by 2020. The recast RED 2018/2001/EU entered into force, and it moved the legal framework to 2030. Also, it sets a new binding renewable energy target for the EU in 2030 of 32% (European Commission, 2020c).

In the 2009 RED, the UK sets a target to achieve 15% of its energy consumption from renewable sources by 2020. This compares to only 1.5% in 2005. The insignificant increase in renewable energy use led to a much greater level of deployment over subsequent decades to meet the target. The analysis indicates that delivering 15% renewable energy by 2020 is feasible through domestic action and could be achieved with different proportions of energy consumption in each sector coming from renewables (European Commission, 2020c). By 2030, wind and solar are expected to reach above 50%, more than in any other country. The UK Clean Growth Strategy puts energy technology and innovation at the center of its decarbonization policy (European Commission, 2020c).

According to the United States Energy Information Administration (U.S. Energy Information Administration, 2020a), the electricity demand grows modestly while favorable costs for renewables result in natural gas and renewables as the primary sources of new generation capacity through 2050. The U.S. Environmental Protection Agency (EPA) issued the final Affordable Clean Energy (ACE) rule in June 2019 as the replacement for the Clean Power Plan (CPP). ACE, issued under the authority of the Clean Air Act, Sec. 111(d), addresses carbon dioxide (CO_2) emissions reduction requirements from existing electric generating units. The rule defines the "best system of emission reduction" (BSER) for existing power plants as onsite, heat rate efficiency improvements. The rule provides guidelines for states to use when developing plans to limit CO_2 emissions at existing coal-fired power plants but does not set technology-specific emissions standards (Ejemeyovwi *et al.*, 2018). The AEO2020 cases include the implementation of ACE by requiring all coal-fired power plants with heat rate improvement options available to undertake the upgrade or retire by 2025, based on an earlier analysis of heat rate improvement potential at existing plants. The year 2025 is an approximation taken from EPA's ACE Rule regulatory impact analysis for when the standards of performance under the final rule might be implemented.

At a point, it became a norm to find out means of generating clean and renewable energy globally, which requires certain mechanisms to drive its course. Only a few countries did not tap into this environmentally clean form of energy. Africa is not left out in this global energy revolution (Nweke-Eze, 2021). Africa's access to fossil-based energy sources can be traced back to Africa's continued dependence on oil, gas, and coal for energy, with very negligible interest in the use of renewable energy. Notably, this has brought about a drawback in terms of social, economic, and environmental sustainability. Tackling the energy challenge on the continent, therefore, requires a firm commitment to the accelerated use of modern renewable energy sources.

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In Africa, countries like Egypt, Ethiopia, Kenya, Morocco, and South Africa are leading this effort, while some of Africa's smaller countries including Cabe Verde, Djibouti, Eswatini, Rwanda, and Malawi have also set ambitious renewable energy targets (Kühnen *et al.*, 2019). Other African countries are following suit, and renewable energy is on the rise across the continent (International Renewable Energy Agency-IRENA, 2015). International Renewable Energy Agency-IRENA (International Renewable Energy Agency-IRENA, 2015) further stated that Africa would require scaling up capital market financing and development bank financing for infrastructure alongside country-by-country assessment of supply, demand, renewable energy potential, and technology prospects. African governments could further accelerate the Program for Infrastructure Development in Africa (PIDA) to attain sustainable development in the energy sector. Also, there is a critical requirement for a legal framework on biomass in Africa. Biogas is another wellspring of energy that is gotten from natural and disposed of materials like animal defecation, decomposable assembling, and homegrown undesirable strong materials (Oke, 2013). Biodiesel is created by changing over oil-bearing harvests like coconut, soya, palm, rapeseed, and sunflower to methyl esters to mix with regular diesel. Biomass as a sustainable power source can advance a consistent power supply to the country inhabitants.

Among the few empirical studies on biomass energy sourcing, utilization, impact, and development, Bildirici and Ozaksoy (2014) examined the connection between biomass energy utilization, oil costs, and monetary development. This paper zeroed in on the relationship since it was acknowledged that biomass energy utilization is influenced by monetary development and the oil cost. On a related note, Bildirici and Ozaksoy (Egbetokun *et al.*, 2018) surveyed the association between oil expenses and biomass energy use was researched using the BDS test, non-linear ARDL approach, and two non-direct Granger cointegration systems for the hour of 1973–2012 in the SSA. The augmented non-linear Granger causality test made by this paper concluded there is a unidirectional Granger causality association between oil cost and biomass energy use in the asymmetric case for positive and negative crude petrol esteem changes in the short-run and strong causality structures.

Öztürk and Bilgili (2015) explored long-run elements of economic growth and biomass utilization nexus by applying dynamic panel investigations for 51 sub-Sahara African nations for the 1980–2009 period. The outcomes show biomass utilization, transparency, and populace have a force on financial development in African nations. Bilgili and Öztürk (2015) clarified that elements of biomass energy utilization impacted the gross domestic products through both homogeneous and heterogeneous difference structures for the G7 nations. The evaluations affirm the development theory that recognizes the constructive outcomes of biomass energy utilization on financial development in G7 nations and biomass energy utilization upgrades economic growth.

The above is essential as environmental quality is a public good that requires global coordination, collaboration, and effort. Individual and country activities will have an implication for the local and global environment. However, African countries that need to achieve a high economic growth rate to converge with developed economies will need to do so while mitigating carbon emissions (Nweke-Eze, 2021). Also, the strong institutional quality will shift the frontier of the economic

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growth-environmental sustainability relationship such that a high economic growth rate will be achieved at a lower environmental degradation. This will require an effective institutional and environmental framework. In this wise, the quality of institutions will augment the elasticities between economic growth and environment and energy. Energy sources contribute to economic growth and environmental degradation (Ejemeyovwi *et al.*, 2019). Due to limited electricity access, biomass dominates the energy supply in both urban and rural Africa[2] albeit at a low scale. Transition to low-environmental impact growth and energy sources will require improved institutions. This is brought to bear in this chapter.

7.3 METHOD OF ANALYSIS

7.3.1 Empirical model and estimation technique

The study adopts the models of Fu *et al.* (2021). The implicit form of the model is specified as follows:

$$Cle = f(Inst, Envqlty, Ecogrth), \tag{7.1}$$

where *Cle* stands for clean energy, *Inst* is for institutions, represented by the rule of law, voice and accountability, political stability, and the absence of violence and government effectiveness. *Envqlty* stands for environmental quality, represented by carbon emission, which is measured in metric tons following Ejemeyovwi *et al.* (2018). The explicit form of Eq. (7.1) is stated as

$$Y^n = \alpha + \beta_1.Inst_{it} + \beta_2.Envqlty_{it} + \beta_3.Ecogrth_{it} + \varepsilon_t. \tag{7.2}$$

Note: α is the intercept, β_1 represents the coefficient of institutions, β_2 is the coefficient of environmental quality, β_4 is the coefficient of economic growth, and ε is the error term.

In estimating the model, the study employs the Bayesian Vector Autoregressive (BVAR), developed by Litterman (1980), which is a method applied to the standard VAR to enable it to overcome weaknesses possessed in the standard VAR technique. BVAR models have been established to let modelers signify their beliefs more precisely by specifying hyperparameters and to combine those beliefs with the information in historical data, in line with the standard VAR procedure. The BVAR method builds on the original VAR models, which constitute imprecise limitations on the VAR coefficients through the use of hyperparameters. Also, the BVAR caters to possible endogeneity and other econometric violations. Ciccarelli and Rebucci (2003) presents a BVAR model in the subsequent form using a more compacted framework of Eq. (7.3),

$$Y_t = X_t\beta + \varepsilon_t, \tag{7.3}$$
$$X_t = (I_n\tilde{O}W_{t-1}) : \text{nxnk matrix},$$

[2] Africa Progress Report 2015, Power People Planet: Seizing Africa's Energy and Climate Opportunities.

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$W_{t-1} = (Y'_{t-1}, Y'_{t-2}, \ldots, Z'_t)'$: kx1 vector,
$\beta = \text{vec}(\beta_1, \beta_2, \ldots, \beta_p, D)$: nkx1 vector,

where β is the unknown parameter of the model to be estimated.

To estimate Eq. (7.3) employing BVAR, the likelihood function of the allied probability density function is expressed in the form

$$L(Y/\beta, \sum) \propto \left|\sum\right|^{-T/2} \{-1/2 \sum (Y_t - X_t\beta)' \sum^{-1} (Y_t - X_t\beta)\}. \tag{7.4}$$

Furthermore, following the pattern of Alege and Ogundipe (2009), the joint prior distribution of the parameters is $p(\beta, \sum)$, while the joint posterior distribution of the parameters conditional on the data is found using the Bayes formula written as follows:

$$p(\beta, \sum/Y) = p(\beta, \sum) L\left(Y/\beta \sum\right),$$
$$(Y) \propto p(\beta, \sum) L(Y/\beta, \sum).$$

The conditional probability, the joint probability density function (pdf) of the data, and the parameters $p(\beta, \sum, Y)$ are written as

$$\begin{aligned} p(\beta, \sum, Y) &= L(Y/\beta, \sum)\, p(\beta, \sum) \\ &= p(\beta, \sum/Y) p(Y), \end{aligned}$$

Given $p(\beta, \sum/Y)$, the marginal posterior distribution conditional on the data $p(\sum/Y)$ and $p(\beta/Y)$ can be gotten by incorporating out β and $\sum$ from $p(\beta, \sum/Y)$, correspondingly. The location and dispersion of $p(\sum/Y)$ and $p(\beta/Y)$ are analyzed to result in the estimate of the parameters of interest and measures of precision comparable to those obtained by using a classical approach to the estimation of the parameters, which is the adopted approach.

7.3.2 Data and variable description

Data utilized were from 2000 to 2019 for 46 SSA countries as informed by available data. The countries include Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central Africa Republic, Chad, Comoros, Congo, Democratic Republic of Congo, Cote D' Ivoire, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, and Guinea Bissau. Others are Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, South Africa, South Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe. The description of variables is presented in Table 7.1.

The specific description of variables utilized in the study is found in Table 7.1. The table gives a description of the variables in terms of the proxies used to capture the various variables (dependent and

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Table 7.1
Summary representation of model.

S/N	Code	Variable	Detail	Measure	Data Source
1	Clean energy	Clean energy for domestic use	the proportion of total population primarily using clean fuels and technologies for domestic use	Percentage of population	World Bank (2020a)
2	Inst	Institutions	Political institutions	Unit	World Bank (2020b)
2a	ROL	Rule of law	Alludes to an administration dependent on standards of law and not of men	Unit	World Bank (2020b)
2b	VOA	Voice and accountability	Reflects perceptions of the extent to which a country's citizens are able to participate in selecting their government.	Unit	World Bank (2020b)
2c	PSAT	Political stability and absence of violence	Perceptions of the likelihood that the government would get destabilized/ overthrown by unconstitutional/violet means	Unit	World Bank (2020b)
2d	GE	Government effectiveness	Refers to the quality of public services	Unit	World Bank (2020b)
3.	Envqlty	Environmental quality–carbon emissions	Waste emissions from the use of non-renewable energy sources	Metric tons *per capita*	World Bank (2020a)
4.	Ecogrth	Economic growth–GDP growth rate	Refers to the rate of growth of the gross domestic product	Percentage	World Bank (2020a)

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independent) and their *a priori* expectation for each variable based on theoretic intuitions, alongside the kind of association that occurs amid each explanatory variable in addition to the dependent variable.

7.4 RESULTS AND DISCUSSION

The Bayesian vector autoregressive (BVAR) model estimation findings are presented in Fig. 7.1 and Table 7.2. The impulse response function (IRF) result indicates that clean energy for domestic use responds to a positive one standard deviation shock from rule of law, regulatory quality, voice and accountability, and government effectiveness in varying magnitude of impact. However, the relationship was overall positive and significant, which followed *a priori* expectation.

For the first institutional measure, Fig. 7.1 shows that a significant positive increase in access to clean energy for domestic use is expected as a result of the introduction of a one standard deviation shock to the institution. This increase is evident in Table 7.2, which shows that in the 1st period, clean energy recorded 0.0036 units, while in the 10th period, 0.0685 was observed. This finding implies that an

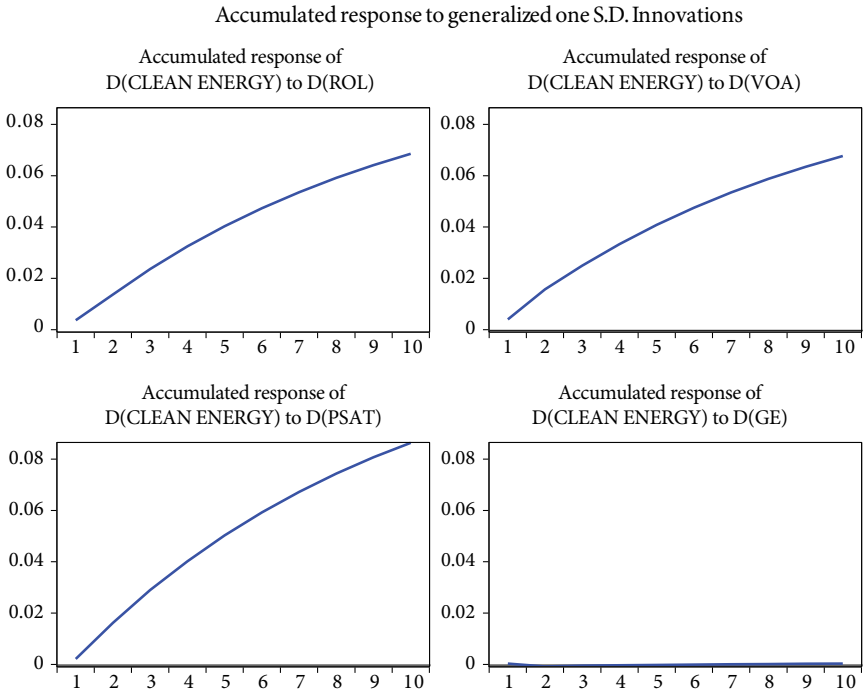
Accumulated response to generalized one S.D. Innovations
Accumulated response of D(CLEAN ENERGY) to D(ROL)
Accumulated response of D(CLEAN ENERGY) to D(VOA)
Accumulated response of D(CLEAN ENERGY) to D(PSAT)
Accumulated response of D(CLEAN ENERGY) to D(GE)
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9 10

FIG. 7.1
Individual response of renewable energy consumption to institutional variables' shocks. The authors' computation using Eviews 10.

improvement in the rule of law within Africa would play a significant positive role in increasing access to clean energy for domestic use. Practically, the rule of law is concerned with the development of sound policies and regulations that promote development in African nations, and in this case, sound policies are expected to be strategically designed, implemented, and regularly updated to ensure that there is increased access to clean energy.

The BVAR simulation produced similar results for voice, accountability, and political stability by the absence of violence shocks. The variables also were in line with *a priori* expected. Figure 7.1 reported that on average, a significant positive increase in access to clean energy for domestic use is spurred as a result of the introduction of a one standard deviation shock to voice, accountability, and political stability with an absence of violence shocks. This increase is also evident in Table 7.2, which shows that for voice and accountability, in the 1st period, "0.0040 units" was observed while in the 10th period, 0.0677 was observed.

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Table 7.2
Individual response of renewable energy consumption to institutional variables' shock.

Period	Rule of law	Voice and accountability	Political stability and absence of violence (PSAT)	Government effectiveness
1	0.0036	0.0040	0.0021	0.000 3
2	0.0136	0.0157	0.0161	−0.000 7
3	0.0235	0.0249	0.0289	−0.000 5
4	0.0324	0.0333	0.0401	−0.000 3
5	0.0402	0.0408	0.0502	−0.000 2
6	0.0473	0.0474	0.0592	−0.000 08
7	0.0535	0.0534	0.0672	0.000 03
8	0.0591	0.0587	0.0743	0.000 13
9	0.0641	0.0634	0.0807	0.000 22
10	0.0685	0.0677	0.0863	0.000 30

With regard to the effect of positive shocks from "political stability" with the absence of violence shocks, on access to clean energy for domestic use, at the 1st period, "0.0021 units" was recorded while at the 10th period, "0.0863 units" was observed. Voice and accountability are concerned with the freedom of the citizens to express themselves and associate, while the political stability with an absence of violence is concerned with the existence or non-existence of terrorism and politically motivated violence. A positive and significant increase in voice and accountability ensures that issues experienced in the utilization and production of clean energy for domestic use are free communication to the involved parties and more importantly, their voices are listened to, and political stability issues are resolved. Political stability, on the other hand, ensures that there is a serene environment to ensure that the processes involved in the production and distribution of clean energy for domestic use are unperturbed.

The study also finds that government effectiveness posits a positive but not too significant relationship with access to clean energy for domestic use. The effect on access to clean energy for domestic use as a result of a one standard deviation shock from government effectiveness was relatively minimal compared to the findings of the other institutional variables considered in this study. Drawing from Table 7.2 and Fig. 7.1, in the 1st period, access to clean energy for domestic use responded to the shock by an increase to 0.0003 units, while in the 10th period, 0.000 30 was observed as the response to the government effectiveness shock. This finding also follows *a priori* expectation and makes economic sense as an increase in the effectiveness of Africa's governments' while carrying out their responsibilities would ensure that there is increased access to clean fuel for domestic use.

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Drawing from the findings of the study, it is expedient to note that institutional framework development is a necessity for ensuring clean energy access in Africa. Specifically, the focus of the institutional framework should be on rule of law, voice and accountability, political stability and absence of violence, and government effectiveness. This is necessary because an institutionally developed environment directs policies from favoring access to non-renewable energy to favoring access to clean energy. The policy development will ensure that they increase demand for clean energy and, on the supply side, provide incentives for the producers of clean energy such as biomass production. Notably, some recently recommended clean biomass energy that sustained community-wide use includes biogas, LPG ethanol, and electricity, improving biomass stoves (Bruce *et al.*, 2015; and Pope *et al.*, 2017).

There is potential for development and value-added in Africa if institutional frameworks are tailored toward driving an increase in the interest of producers to focus on clean energy development such as biomass energy development. This is because most African countries are blessed with the resources needed for the creation of biomass energy such as wood and other organic matter, hence, the cost of producing and refining energy from these materials will be relatively cheap compared to the cost of producing energy from fossil fuels. Furthermore, the focus of institutional framework to clean energy will reduce the need for oil-producing African countries to export the fossil fuels in their primary state at a cheap price and import the final products at a more expensive price, thus, having a massive net loss on the energy gains and harming the foreign exchange value of our domestic currency.

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7.5 CONCLUSIONS

Given the emerging relevance and debate on biomass energy, this chapter examined the nexus between institutions and clean fuels for domestic use in Africa. The study utilized panel data for the 54 countries in Africa within the period 2000–2019. One of the significant findings from the study is that shocks from rule of law, voice and accountability, political stability with the absence of violence, and government effectiveness positively drive access to clean energy for domestic use in Africa. However, the impact observed for government effectiveness was relatively small compared to the other institutional variables with more significant impacts.

Expanding Africa's clean energy access is a need and to make biomass energy a sustainable option, an all-encompassing approach would be required. This incorporates contemplations of the full biomass inventory network, the nature of biomass creation, the change of biomass into other energy structures, and the board of bioenergy creation framework in a practical way with minimum effect on the climate. In this manner, it is about time that approaches, targets, techniques are rehearsed explicitly to the biomass area inside the control of Energy strategic agencies. Other remarkable territories incorporate existing National offices just as legitimate systems applicable to the institutional courses of action.

In line with the findings, this chapter recommends that to significantly improve the access to clean fuels for domestic use in Africa, significant improvements in the institutional framework present in

African countries are necessary. The institutional framework constitutes the rule of law, voice and accountability, political stability with the absence of violence, and government effectiveness. These improvements are necessary, having simulated and discovered their significant role in ensuring increased access to clean fuel for energy use.

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CHAPTER

8 TIDAL AND OCEAN WAVE'S ENERGY

Johra Khan

Khan, J., "Tidal and ocean wave's energy," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 8-1–8-16.

8.1 INTRODUCTION

Renewable energy is the most researched and in-demand form of energy. The 21st century is considered as the age of alternate energy sources with a special focus on nuclear and renewable energy sources (Antonio 2010; and Smith *et al.*, 2013). The use of fossil fuels is not only a heavy burden on the economy but also on the environment, in the form of pollution and global warming (Drew *et al.*, 2009). Coal and petroleum contribute the largest part in electricity generation for industries and as per EIA2020 (Leaver, 2019) the demand for non-renewable energy sources will decrease by 9% due to the COVID-19 pandemic (Pegels, 2010; and MacGregor, 2016), but still, it is the most used form of electricity generation (Mork *et al.*, 2010). As per the annual energy outlook for 2020, the dependence and use of renewable energy will increase up to 38% by 2040 (Sieminski, 2015; and Conti *et al.*, 2016). Renewable energy sources are very useful for the sustainable development of humans without affecting the ecological cycle (Metayer *et al.*, 2015; and Gilbert and Sovacool, 2016). As these sources never deplete with time and can be easily found in nature, they are the most studied and researched energy alternatives (Panwar *et al.*, 2011). More than 70% of the earth's surface is surrounded by water, out of which most is found in the ocean (Cunliffe *et al.*, 2013). Oceans are the biggest collector of solar energy and heat from the sun and the gravitational pull from the moon causing tides and ocean waves (Ghosh and Prelas, 2011). Although all renewable energy sources are very important, ocean energy is the most promising due to its abundance, easy source predictability, and low environmental impact (Alrikabi, 2014). New developments in technology taking place each day increase the possibility to use ocean energy to generate electricity (Hasan *et al.*, 2018; and Khojasteh *et al.*, 2018). Many industries that are working on ocean energy utilization are focusing on developing low-cost technology and devices to generate electricity from ocean waves and tidal energy that can be converted into electricity and at the same time on devices that can use this energy for production or running machines (Segura *et al.*, 2017).

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Tidal energy, a form of ocean energy, was first used to run a tide mill on the seashores of France, Spain, and Britain around 800 A.D. (Rourke *et al.*, 2010). These tide mills were structured in a pond that receives tide passing through a lock and washes away the water wheel while on low tide (Polagye *et al.*, 2011). The moving water wheel generates power used to mill grain and the energy was enough to work for up to 3 h twice a day (Blunden and Bahaj, 2007). With the development of human civilization and increased energy demand there is a need for improvement in power generation using tidal energy (Esteban and Leary, 2012). St. Malo, France was the first tidal power plant that was able to produce enough energy to light 240 MW fluorescent lamps (Johnstone *et al.*, 2013; and Yang *et al.*, 2013). Countries like France, Canada, China, Switzerland, and the UK established many commercial tidal barrages to utilize tidal energy forms (Bedard *et al.*, 2007; Brekken *et al.*, 2009; and Thomson *et al.*, 2012).

8.2 NATURE OF TIDAL POWER

The formation of tides in the ocean occurs under the influence of gravitational pull from the sun and moon, due to which water in the ocean rises and falls, creating tides (Wirgin *et al.*, 2012). Tides consist of vertical and horizontal water movements forming tidal currents. The vertical rise and fall of tides are known as the tidal range, whereas the horizontal movement is known as the tidal current (Etemadi *et al.*, 2011). The tidal range consists of potential energy and the tidal current consists of kinetic energy. To use this energy, the first tidal power plant was made available online in 1984 located in the Bay of Fundy (Tsai and Chen, 2014) and on the Annapolis River, Canada. Its installation capacity was 20 MW (Doelle *et al.*, 2006; and Khan *et al.*, 2018). The current was not only generated by tides but also from wind, temperature, and salinity differences in ocean water (Ringwood *et al.*, 2014). Ocean wave energy utilization to generate electricity is also the center of many types of research (António, 2008).

The use of tidal power (P) is always proportional to water head difference ($H2$) assisted between upstream and downstream sides of the impoundment and the impounded dampened plan surface area (A) as demonstrated in Eq. (8.1) (Alvarez *et al.*, 2016; and Angeloudis *et al.*, 2016),

$$PP \propto A \times H. \tag{8.1}$$

The immediate power of a tidal tributary can be expressed as in Eq. (8.2), where P is the power in watts (W), C_p is the device efficiency, ρ is the density of water, where $\rho = 1025$ kg/m^3, A is the area of cross section in m^2, and v is the current velocity in m/s,

$$P = \frac{1}{2} Cp \times A \times v^3. \tag{8.2}$$

8.2.1 Exploitation of tidal power

To exploit a power source, its potential must be well understood and documented in a global scenario to bring maximum use of it (del Rosario *et al.*, 2006; and Elghali *et al.*, 2007). As per estimates done

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in different research studies, the total global tidal power is around 2.5 TW (terawatts) and around 500–1000 TWH (terawatt hours) per annum (Walters *et al.*, 2013). The total tidal power available for harvesting from areas around the ocean coast is around 1 TW (Ren *et al.*, 2017). As per different studies, this tidal power is bigger than the capacity of tidal barrages (Ren *et al.*, 2017).

8.2.1.1 Tidal barrages

A tidal barrage is a dam constructed on a basin or in an estuary that harnesses energy from low and high tide to produce electric energy (Pontes and Falcao, 2001). Many countries like Europe, North America, and Asia are experimenting and developing this technique since 1966 (Tousif and Taslim, 2011). The different models of tidal barrages include (i) one-way (ebb-only) and (ii) two-way (flood-ebb) (Roberts *et al.*, 2016). Some of the well-known tidal barrages are Sihwa Lake Tidal Power Station (Boretti, 2020), Korea with a capacity of 254 MW of power capacity (Zaidi *et al.*, 2021), Lab Rance tidal power station, France (Angeloudis *et al.*, 2020) with 240 MW energy generation capacity, Annapolis Royal tidal power plant in Nova Scotia, Canada with the capacity of 20 MW, and Jiangxia tidal power plant, Zhejiang Province, China with the capacity of 4.1 MW, and many more in Russia and South Korea (Bryden, 2013; Todeschini, 2017; and Boretti, 2020).

8.2.1.2 Tidal turbines

Tidal power is generated by using current kinetic energy to generate electric power (Lynn, 2013) (Fig. 8.1). The tidal current devices consist of many different types of turbines some of which are

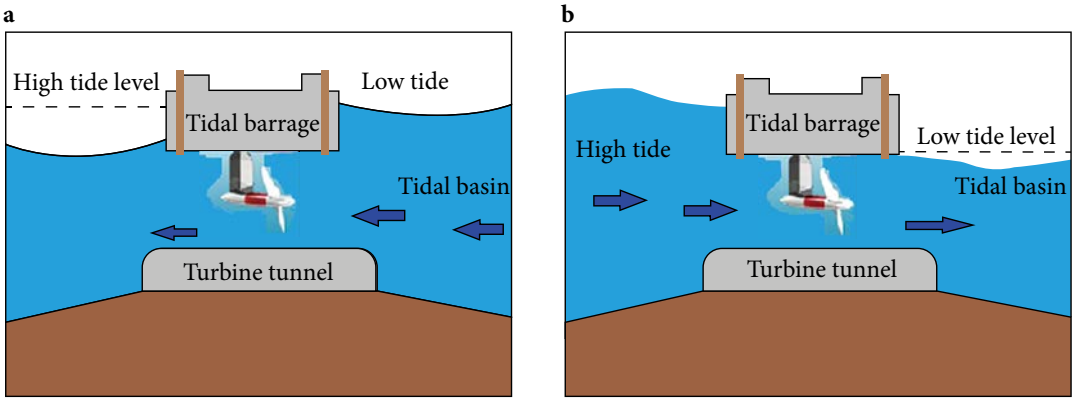

FIG. 8.1
Tidal barrage structure; (a) incoming tide, (b) outgoing tide.

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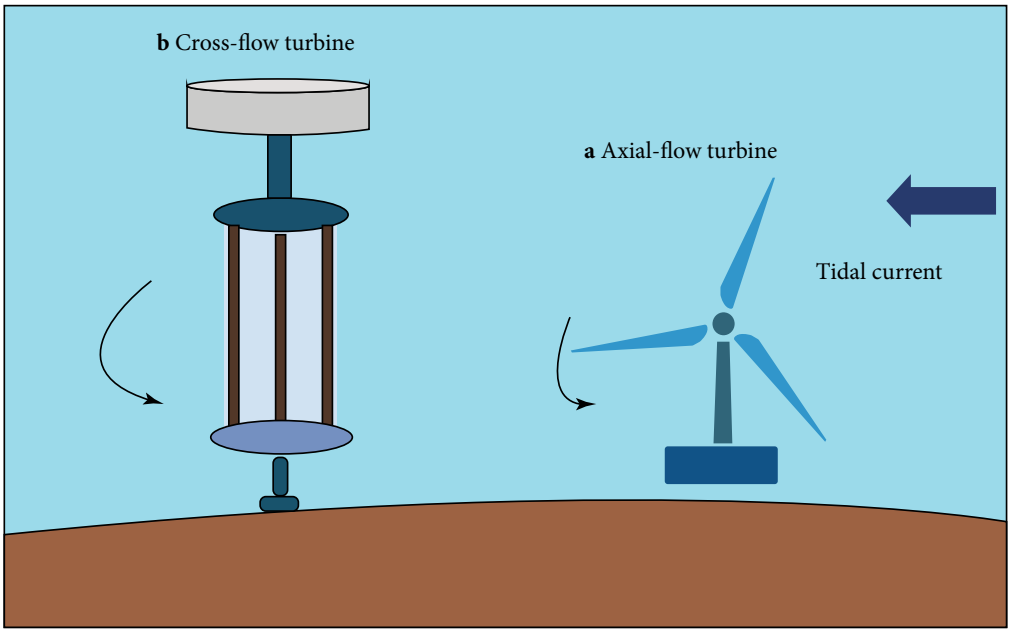

FIG. 8.2
Different types of tidal turbines. (a) Axial flow turbine and (b) crossflow turbine.

a. Axial flow turbine: Axial flow turbine is made of two to three blades rotating on a rotor that moves in the direction of water current (Kacker and Okapuu, 1982). The movement of a turbine is always parallel to the water current and the blades rotate the generator connected to them to produce power (Boudreau and Dumas, 2017) (Fig. 8.2).
b. Cross-flow turbine: The second type of turbine used is the cross-flow turbine. The design of this turbine is to accelerate the velocity of tidal water (Consul *et al.*, 2009). Its structure turbine consists of three blades moving on a vertical shaft (Consul *et al.*, 2009; and Sinagra *et al.*, 2014). The rotation of the shaft is perpendicular to the water current of the stream. The moving tidal current moves rotor to generate electricity (Olgun, 1998). To increase the capacity of the turbine and to increase electricity production, an oscillating hydrofoil device was introduced. This device works on the drag force of a wing-like hydroplane to move the rotor up and down, which converts mechanical energy to electrical energy. Oscillatory motion can be controlled by changing the direction of blades about inward water movement (Fiuzat and Akerkar, 1991; and Desai and Aziz, 1994).
c. Deltastream turbine: It consists of three blades on a horizontal turbine axis with a diameter of 15 m. It is situated on a triangular structure with a low gravitational pull to stabilize the turbine in the tidal current. Tidal Energy Ltd developed the first deltastream turbine in 2011 that was funded by ECO2 (Zanetti, 2013) (Fig. 8.3).

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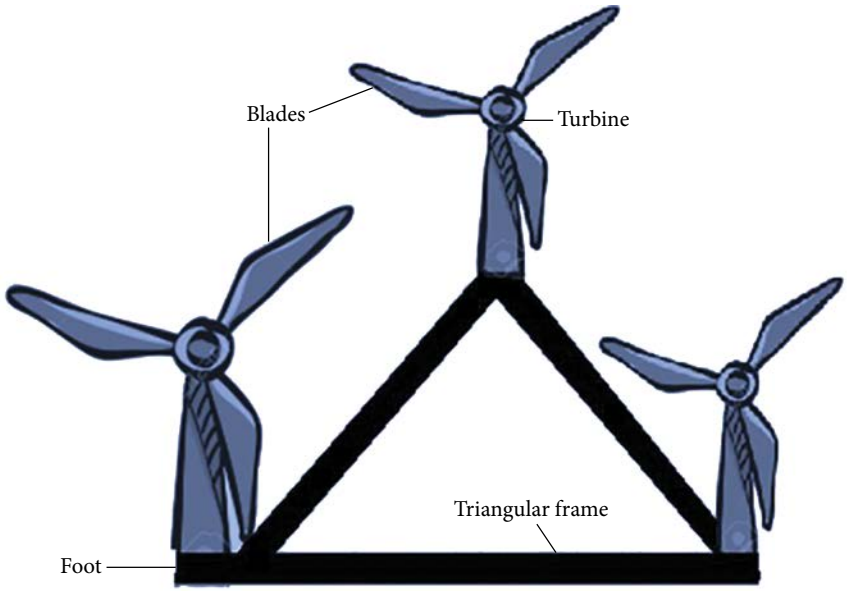

FIG. 8.3
Deltastream turbine and its parts.

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8.3 TYPES OF WAVE POWER PLANTS

The ocean waves on the surface when captured and converted to electric energy are known as wave power (Lagoun *et al.*, 2010). As per an estimate, the total wave energy that can be generated is around 8×10^6 TWH/year, which is a hundred times the total hydroelectric energy produced from all plants on earth. Out of this huge amount of energy, only 10%–15% can be converted to energy due to various limitations (Lekube *et al.*, 2016). In Europe, only 320 GW of energy is generated from wave, although it can be up to 120 TWH, which need more use of technology and development in devices in use (Falcão, 2003; and Garrido *et al.*, 2012). The classifications of these devices are based on the place of their installation, and power take-off system. Some of these locations are shore-line, near-shore, and off-shore and power take-off systems are classified as oscillating columns of water, wave dragon system, underwater pneumatic system, and oscillating bodies systems. Some of these systems are installed on the sea shoreline and at the bottom of the sea (Amarasekara *et al.*, 2014).

8.3.1 Different power plant

a. Oscillating water column (OWC): It consists of a chamber at the shoreline coast. During wave motions, the air pocket up and down at the backside of the equator reaches the turbine. While

returning to the sea, the wave creates air depression that moves the turbine in the opposite direction to wave motion (Evans, 1978; and Morris-Thomas *et al.*, 2007). OWC consists of a chamber for air collection and a power taker off the system, which converts mechanical energy to electric energy (El Tawil *et al.*, 2017). This is a type of shoreline located in power plants.

b. Pendulum system (PS): It is another shore-line system that consists of a concrete box with a parallel pipe in it that was open on one side to the sea (Yurchenko and Alevras, 2018). The opening has a pendulum flap on the opening, which moves by waves. The movement of the pendulum powers a hydraulic pump that generates electricity (Yurchenko and Alevras, 2013).

c. Wave dragon system: These are small floating slack-moored structures able to convert wave power to electricity. They are placed in a group of around 200 dragons that results in a power park being able to generate energy equal to a fossil fuel-run plant (Kofoed *et al.*, 2006; and Diaconu and Rusu, 2013). The structure consists of a ramp and a reservoir. A wave moves on-ramp and the water returns through a hydroturbine which converts wave energy into electricity (Kofoed *et al.*, 2007; and Rodrigues, 2008). It is a type of ear-shore power plant.

d. Pelamis (snake-like) energy converter: This system consists of six enunciated cylindrical structures of 3.5 m diameter and 30 m high. These floating articulated cylinders are connected to four cylinders of about 3.5 m diameter and 5 m long (Parker *et al.*, 2007; and Thomson *et al.*, 2019). These are included in off-shore power plants with a total length of this structure is around 140 m and their 2/3rd part remains in deep water. As the wave passes, these structures move from side to side and up-down like a snake. A hydraulic motor present in this structure converts wave energy to electric power as passes it to the power grid via a power cable (Prakash *et al.*, 2016).

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8.4 WAVE ENERGY DESIGNS AND TECHNICAL IMPROVEMENTS

Being the largest source of renewable energy, wave energy faced a moment of a setback in the early years of development due to slow development and no concrete design and technology development (Falnes and Løvseth, 1991). More concern for the environment and increasing oil crises reintroduced the need for modifications in design and technology for wave energy (NikWB *et al.*, 2011). Wave energy design can be classified into three major types; attenuator, point absorber, and terminator (Hayward and Osman, 2011).

1. Attenuator: This device lies parallel to the biggest wave direction and it moves on waves to generate electricity (Xie and Zuo, 2013). Pelamis (P1), the prototype was tested at EMEC's test site at Billia Croo, in 2004. Pelamis is a tube-like structure, which is 120 m long with a 3.5 m diameter. It is divided into four sections and its head contains a turbine that connects the energy into electricity (Al Karim *et al.*, 2015). The 2nd generation P2 came between 2004 and 2007 with five connected tubes with more flexibility that can bend with wave movement (Pedersen *et al.*, 2016). The hydraulic ram harnesses the energy in movement and is converted to electricity by a generator located inside the head of the device. The approximate with of this prototype was around 1350 tonnes (Dang *et al.*, 2019).

2. Point absorber: A device of small length concerning the incident wavelength. This device keeps moving up and down with waves either on the surface of the sea or sometimes at the bottom according to wave pressure (Budar and Falnes, 1975; and Sjökvist *et al.*, 2014). Powerbuoys made by Ocean Power Technologies are one example of point absorber devices. These floating devices' absorbers are attached to a cylindrical structure with a bottom; the second part includes a compartment that moves by the energy of wave motion to generate electricity (Peiffer *et al.*, 2011; and Bozzi *et al.*, 2013).
3. Terminator: This device floats parallel to the wave-front or perpendicular to wave motion, which captures wave energy. Salter Duck is a terminator device designed by the University of Edinburg (Czech and Bauer, 2012; and Rusu and Onea, 2017).

8.4.1 Technology developments

Technology development is very necessary for getting better energy production. U.S. Space Agency (Prakash *et al.*, 2016) developed a technology known as the Technology Readiness Level (TRL), which consists of nine levels of development (Straub, 2015). This approach was adopted to develop buoyant type WECs (wave energy converters) for assessing the financial and technical risk in the device developmental process. The 12 guidelines developed by the European Marine Energy Centre (EMEC), and the United Kingdom added additional important topics in WEC like resource assessment for tidal energy, maintenance, manufacturing, production rate, etc. (Magagna and Uihlein, 2015). The international energy Agency–Ocean energy system group adopted the five-stage approach known as "best practices" in 2009 (Fig. 8.4). These five-stage approaches are as follows (Wolfram, 2006; and Ingram *et al.*, 2011):

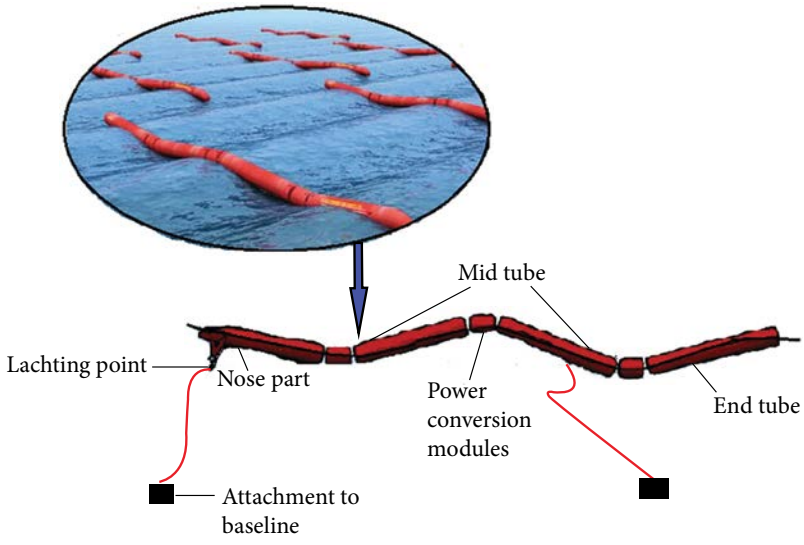

FIG. 8.4
Structure of Pelamis.

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1. Proof of concept: This stage deals with design validation of the basic PTO model mechanism, development of the mathematic model, design optimization, and device development (Greaves and Iglesias, 2018; and Segura *et al.*, 2018).
2. Design validation: This is the study of the design and its practicability, through verification of potential performance in the sea with laboratory testing on set parameters (Leary and Esteban, 2009).
3. Process model: The prototype is used for sea trials at test sites in real environmental conditions and verification of all their systems and sub-systems. This step also evaluates energy production, control strategies, and their effect on power production. It also evaluates the effect of the device on the environment, manufacturing, and installation methods (Soukissian *et al.*, 2017).
4. Prototype model: This step deals with the development of a full-size prototype device, grid connection, survival in environmental conditions, mooring, and cable connection-related issues are studied.
5. Demonstration of technology: From (3)–(5), devices are evaluated based on their performance, array integration, and economic feasibility. This five-stage program provides a logical method to test, optimize, and validate technology and devices for WEC. It also helps to avoid unexpected or unsatisfactory results. During development, if any modification is needed, then the process goes back to the last stage before validation and proceeds to the next stage. During the last years, a lot of difficulties and failures were faced in handling issues related to technology development. Many important concerns have been highlighted in technology divergence and performance, which focus on the need of assessing WECs on set standards, analysis, and technology transfer between different countries with global cooperation in technology development (Table 8.1).

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Table 8.1
Different stages and developmental steps of wave technology.

Stage	Scale guidelines	Stage of development	References
Proof of concept	Small; 1:25–100	1. Confirmation of operation	Ehsan *et al.* (2000) and Mwasilu and Jung (2019)
		2. Performance	Payne *et al.* (2007) and Sheng (2019)
		3. Device optimization	Babarit *et al.* (2008)
Design validation	Medium; 1:10–25	4. Sub-system analysis	Cruz (2007)
Process model	Large; 1:2–5	5. Bench sub-assembly test	Valério *et al.* (2007)
		6. Prototype testing in sea	
Prototype model	Prototype; 1:1–2	7. Solo, sheltered, grid, emulator	McCann and Bell (2017)
		8. Exposed grid, solo	
Demonstration of technology	Full; 1:1	9. Multi-device array testing	Morris *et al.* (2016)

8.5 OCEAN WAVE ENERGY POTENTIAL

To calculate the ocean wave energy potential, different models with temporal and spatial variability are used around the globe by different researchers. The wave energy potential of the Black Sea was evaluated by using a spectral wave model of the 3rd generation with the help of the European Centre for Medium-Range Weather Forecast (ECMWF) (Mendes *et al.*, 2012). A wave power atlas with average time and wave power was made with a table showing data related to wave roses and power distribution in time-variant heights at different regions (Ozdamar *et al.*, 2004). These data showed a decrease in wave energy potential from west to east with a variation of 1.9–7.6 kW/m (Bernard *et al.*, 2001). ECMWF was also used to assess the wave power potential of Mediterranean Sea basins (Emmanouil *et al.*, 2016). Data of 15 years were generated in the form of wave height and mean wave period. The result showed the active wave power potential at the basin between Nile and Libya border delta. The average height of the wave was around 4 m, whereas the wave energy period was between 4 and 8 s with annual wave energy estimated to be around 5.9 kW/m (Horne and Thorne, 1998).

Tools like scatter diagrams, direction plots help researchers to evaluate the wave energy potential. Many kinds of research show a decrease in wave power during wave travel from offshore to nearshore due to refraction (Wang, 2002). Data related to seasonal and monthly variations are also important to assess resources for continuous energy supply throughtout the year. Some researchers only focus on wave energy potential without an estimation of the tidal wave effect. In a study, the tidal effect was calculated by stimulating tides using the regional ocean modeling system (ROMS) and stimulating waves nearshore technology (SWAN) (Hassan *et al.*, 2014). The study also included one-way coupling to assess the effect of tides on waves. The result showed more than 10% impact of tides on wave energy potential, and tidal current produces more impact in comparison to tidal elevation. The study also concluded that the effect of tides is more on areas with low to medium wave energy sites (Uihlein and Magagna, 2016). A similar study using SWAN was done in Peru with low seasonal variability and found it an advantage for wave energy conversion (Frid *et al.*, 2012). A plot of water depth with wave energy variation was plotted for understanding the requirements of wave energy converter devices in such areas. In India coastal area near Kerala was found very suitable for converter installation that can provide an average of 13 kW/m wave power (Raju and Ravindran, 1997; and Harishma *et al.*, 2020). The average wave power potential was found more on the east coast and along the west coast up to 85% more in comparison to Southern Ocean coasts (Sannasiraj and Sundar, 2016).

8.6 CONCLUSIONS

Wave energy is a significant source of renewable energy. Because of this, there is much ongoing conversation regarding wave energy as a focus of alternate renewable energy research. Certain regions on the globe hold an enormous amount of wave energy, especially in the seashores of Europe, North and

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South America, Australia, South Africa, north of the United Kingdom, and New Zealand. The current technology present is not enough to harness this huge amount of energy due to many shortcomings and less commercialization; therefore, the need for development in devices and technology is the need of today's time. There are many areas of potential improvements, such as the cost of devices, low production rate, adverse environmental conditions, safety, and additional research and development for newer technologies.

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CHAPTER

9 HYDRO- AND GEOTHERMAL ENERGY

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9.1 INTRODUCTION

Reducing the threat of increasing population on the environment is a big challenge (Kling and Rubin, 1997). Steep population growth, urbanization, and human malpractices have exponentially increased the demand for conventional energy and their subsequent unplanned uses affecting the environment every now and then (Murch, 1971). A large fraction of the environmental malpractices includes unnecessary burning of fossil fuel producing a huge amount of greenhouse gases (Small and Kazimi, 2018). A steep rise in carbon footprint has compelled environmental strategists to revisit and explore renewable energy resources on a serious note (Panwar *et al.*, 2011). As a part of that, geothermal and hydrothermal/hydroelectric energies have been explored as an important and abundant source of clean energy. Geothermal energy utilizes the heat stored inside the earth's crust, being regularly produced by radioisotopes through their chemical transformation (Sims, 2008). This energy may be used as an abundant source to heat water, for plantation in green houses, drying crops, heating water at fish farms, and so on (Moya *et al.*, 2018). Hydrothermal energy/hydroelectricity is created from the motion of the water; a large proportion of that kinetic energy is converted to electricity. By controlling the motion of water, additional benefits, such as control over the flood situation and improved water supply for irrigation, could also be derived (Killingtveit, 2019). The following sections provide us insight into hydro- and geothermal energies, the mechanistic and technological details of energy conversion, and managements and applications.

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9.2 ABOUT HYDRO- AND GEOTHERMAL ENERGIES

We face new challenges every day that emerge from the environmental condition of our planet. A major concern for our climate is widespread deforestation, and there is a pressing need to start using green sources that replace the burning of fossil fuels. Geothermal power and hydroelectric power are renewable sources of energy, and "clean" sources of fuel are generated.

Heat deposited deep within the earth or sometimes in hot springs is geothermal energy. The decay of radioactive isotopes, such as uranium, thorium, and potassium, continuously produces this heat. Geothermal heat pump systems can heat and cool buildings and can provide a hot water supply as well. Some of the sources from which greenhouse gases are emitted involve plant processing, seed drying, fish farm water heating, and many other industrial methods. Geothermal energy needs no fuel, and, as a consequence, no emissions of greenhouse gases are produced (Pan *et al.*, 2019).

9.2.1 Hydroelectricity

Hydroelectricity is a source of energy that is produced and converted into electricity by the movement of water (kinetic energy). The continuous motion of the water cycle generates hydroelectric energy, and this is the product of solar heat and the earth's gravitational forces. Through the evaporation of precipitation, the water cycle continues and then it comes back down as rain, hail, or snow. This steady decline in water is what causes the generation of hydroelectricity. Hydropower, thus, is fed by water and propelled by the sun; it is a renewable source of heat. Flood regulation, drainage, and water availability are other advantages provided by hydropower efforts.

9.2.2 Geothermal energy

Geothermal energy is confined to appropriate areas. There are a couple of countries that invest in geothermal energy. Geothermal production in the United States is adequate for around 3×10^6 people. Some western states (California, Idaho, and Utah), Alaska, and Hawaii are home to these geothermal reservoirs (Sun *et al.*, 2018b). However, installing geothermal technology can be expensive, although there are start-ups that claim to have discovered an effective device implementation solution that makes the average price per kilowatt lower than other renewable options. Also, it is known that Iceland has massive geothermal reservoirs. Its geographical location is suitable for geothermal conditions and thus makes it abundant; electricity is inexpensive.

Everywhere now, owing to power plants being installed within dams, many houses and companies generate hydroelectric power. The most commonly used renewable source in the world is hydropower, which accounts for 17% of global energy supply. It is mainly produced by China, followed by Canada, the USA, and Brazil. Remnants of hydroelectric and geothermal energies that need to be built remain economically feasible. There is no question that an improvement in the use of these sustainable resources will, in different ways, benefit our climate (Falcone *et al.*, 2018).

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9.2.3 Uses

A broad range of end-uses, such as area heating and cooling, industry, greenhouses, fish farming, and health spas, may be included in the direct application of geothermal energy. Mostly, it uses modern technologies and straightforward engineering. The direct use of geothermal energy has been demonstrated worldwide in terms of infrastructure, reliability, economics, and environmental acceptability. Bathing/swimming/balneology (42%), space heating (35% of which is 12% with geothermal heat pumps), greenhouses (9%), fish farming (6%), and industry are the major forms of direct use (6%). Direct implementation can use geothermal energy both at high and low temperatures and is much more common in the world than the production of electricity. Direct deployment is, however, more site-specific for the market since long distances from the geothermal site are hardly moved by steam and hot water (Wang *et al.*, 2018). This has helped all countries to use the earth's sun, as needed, for heating and/or cooling. It should be emphasized that heat pumps will essentially be used everywhere. The use of geothermal energy in different ways is enjoyed by citizens in at least 64 countries around the world. However, the scale of usage is very complex. Iceland, which gets 50% of its overall primary energy usage from geothermal energy, the rest from 18% hydropower, 30% oil ,and 2% gas, is the nation with the most significant use of geothermal energy (Sims, 1993).

9.2.4 Present scenario

In Iceland, geothermal energy accounts for 86% of room heating and about 16% of electricity generation (the remainder is hydropower). In greenhouses, industry, fish breeding, snow melting, and swimming, geothermal energy is also used. A variable volume of gas, primarily nitrogen and carbon dioxide with some hydrogen sulfide and lesser proportions of ammonia, arsenic, radon, and boron, is found in geothermal fluids. The quantities rely on the geological conditions of various fields.

Any of the pollutants in the disposal water are condensed and are regularly reinjected into drill holes and thus not discharged into the atmosphere. Gas amounts are generally not dangerous, and the removal of hydrogen sulfide from geothermal steam, for example, is a normal practice in geothermal power plants where the gas content is high (Fridleifsson, 2001).

In the late 1970s, the first was a U.S. Department of Energy initiative for establishment of geothermal plants, which was then followed by two private projects, as already mentioned. The hydrothermal reservoir electricity generation technology with naturally high permeability was already mature by that time and efficient and was in use since 1913. Many of the power plants currently in service are dry steam or flash (single, double, and triple) plants harnessing temperatures above 180 °C. However, with the advancement of binary cycle technologies in which geothermal fluid is used by heat exchangers to heat a process fluid in a closed loop, medium temperature fields are increasingly being used for energy generation or for combined heat and power. In addition, new technologies, including Enhanced Geothermal Systems (EGSs), which are in the demonstration stage, are also being developed of late (https://www.irena.org/geothermal).

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9.3 NATURE OF HYDROELECTRIC ENERGY

Hydroelectric energy, i.e., hydropower, is a renewable energy source where electrical energy is derived from both potential and kinetic energies of confined water moving from high to lower elevation in a dam. Dams are constructed on the river to contain the water flow and reserve for power generation. The technology is very consistent, well established, and widely used. According to the world data of 2016, around 150 countries throughout the world have already developed the infrastructures for hydropower generation and uses (Killingtveit, 2019). This form of energy has a big role in CO_2 reduction from burning fuels to generate thermal electricity (Breeze, 2019). However, there are some key constraints for hydropower generation. These include high initial cost and social and environmental impacts. Apart from that, there are some technical issues. For example, when an organic substrate is decomposed in the dam, a large number of gases, including methane, are readily emitted.

9.3.1 Hydroelectric power plants

In a hydroelectric plant, although alterations of the water flow by damming and diversions are not the only cause for social and environmental problems, they are considered the most common causes globally. The amount of energy obtained from hydroelectric power globally accounts for 2800 TWh, which is about 5% of the total consumed energy Other than the big power systems, small and microsystems are also in operation, which usually runs on the rivers without dams. These provide electricity in the rural area of the developing countries, such as Nepal, Bhutan, etc. Although the manufacturing cost of the hydropower energy is very high, it can generate 30–40/MWh of energy, which is comparable with the energy coming from coal plants (El Bassam *et al.*, 2013). This will be even more relevant and significant once the international carbon trading is enforced. However, during the growth process of a hydroelectric power station, side advantages, such as creating irrigation services, recreational reservoirs, and flood control systems, need to be taken into consideration. Nevertheless, the environmental and social impacts of the construction of large hydropower systems, including those of environmental organizations that typically support renewable energy projects, have raised concerns among the environmentalists time and again.

9.3.2 Generation of hydropower

Around 75% of the world's water reservoirs were initially designed for irrigation, flood control, and urban water supply systems; therefore, minor retrofits for hydropower generation could be added to many of them (Goh, 2019). During the 20th century, hydropower capacity grew strongly and was the only major renewable source of electricity until the later part of that century. The cost of power generating from such sites could range between $20 and $90/MWh, excluding any additional costs necessary for grid connection and distribution of electricity. In remote areas, such costs can be prohibitive, even for mini-grids where no current infrastructure is usable. Emissions of greenhouse

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gases arise from the development of cement used during the building of hydrodams and, in some cases, from the release of methane from reservoirs after vegetation flooding also raises concern. These effects differ greatly with the average ambient temperature and area; therefore, sustainability guidelines have been established to encourage greater environmental and social rehabilitation. In order to drive a turbine connected to an electric generator, hydropower uses water energy flowing from upstream to downstream, thus producing electricity. Without much variance due to constant flow, hydropower is a highly effective and reliable energy source. There is generally a distinction between big hydro- and small hydropower (Breeze, 2018) capacity systems. While large hydropower systems were constructed dated back with a much higher capital cost and environmental and societal impacts, smaller units conversely are more recently designed and implemented with lesser environmental impact and thus are more sustainable in nature.

As mentioned, hydropower imbibes water energy that flows from upstream to downstream to drive a turbine linked to an electric generator and thus produces electricity. Without much difference due to continuous flow, hydropower is a highly effective and reliable energy resource. The energy converted is proportional to the product of the volume flow rate of the water and its pressure head. There is no accepted definition of small and microscale hydropower dimensions to date. Yet, the power generated in a small hydropower unit varies from 2.5 to 25 MW, while it is higher in the case of a larger unit. Run-of-the-river systems, with no dam and water supply, are the traditional micro-hydropower device used to fuel a single house. Grid or stand-alone may be linked to micro-hydropower (off grid) (Idiaghe, 2018) systems in operation.

Around one fourth of the world's hydropower capacity has been used to date. It can supply energy inputs that are strategically high. With a better record in general than diesel or nuclear systems, these massive power plants have proven to be reliable. Hydro plants, however, may be affected by drought. Also, with energy systems containing considerable hydrostorage, support for gas turbines or load shedding is often required during extreme water shortage; thus, often, a strong argument for large-scale hydropower production with large dams has been made on environmental and energy supply grounds (Sims, 1993). If an energy delivery grid includes a large proportion of hydropower, there are three broad techniques available to increase its resilience to hydropower failure caused by drought. The first is to increase the amount of water stored where topography and the climate allow; the second is to create additional capacity for hydropower in new catchments. However, maximum gain can be obtained from the third one, which is a hybrid one that utilizes both thermal and hydropowers that involves maximum utilization of the water supply vis-a-vis runs at a lower overall cost. Since early human cultures, hydropower has been in use. Moving water produces energy harnessing a basic energy conversion technique. Swiftly flowing river serves as a great energy resource. Usually, hydropower operations entail water running through a pipe or penstock before pressing against turbine blades attached to an electric generator and further spinning them. The power of the current adds pressure to spin the turbine-generator to render electricity in a "run-of-the-river environment." Water is stored in reservoirs created by dams in a storage system and released as required. The energy to generate electricity is given by the power of the water generated by water pressure and gravity.

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9.3.3 Advantages of using hydroelectricity

1. Minimum pollution due to no burning of fuels.
2. Renewable source of energy, i.e., water.
3. Emission of greenhouse gases is reduced.
4. Low operation and maintenance cost.
5. Reliable and proven technology.

As most significant hydropower operations are situated on large bodies of water far from the communities that require electricity, the production of long-distance power transmission has been a boon to hydropower growth (Tubert-Brohman *et al.*, 2013).

Cons of power plant that uses coal, oil, and gas fuel are as follows:

1. Using valuable and limited natural resources.
2. Causing huge pollution.
3. To get oil, coal digging must be done.
4. Waste disposal problem in the case of nuclear power plants.

However, there are a few unavoidable disadvantages of hydroelectric power plant, such as

1. huge investment cost,
2. largely depends on precipitation,
3. hampering wildlife and land in some cases,
4. displacing local population, and
5. hampering the aqueous life.

The water or the environment is not poisoned by hydropower. However, by altering the landscape and impacting land use, houses, and natural ecosystems in the dam sector, hydropower plants may have large environmental impacts. A dam and a reservoir are found in most hydroelectric power plants. Such structures can hinder the migration of fish and affect their populations. Operating a hydroelectric power plant can also change the temperature of the water and the flow of the river. Local plants and animals in the river and on land may be affected by these improvements. Reservoirs protect houses, large natural areas, farm property, and archeological sites for humans. Therefore, constructing dams mean relocating people. In certain rivers, methane, a potent greenhouse gas, can also develop and be released into the atmosphere.

9.4 DEVELOPMENT OF HYDROPOWER

Hydroelectric power is the world's most primitive source of renewable energy, generating around 6.3% of the total electricity of the hugely populated country, India, over the last decade. Even after a century

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of proven experience with this reliable renewable resource, there are still important opportunities to extend the hydropower capacity of the nations through non-powered dams and water transmission systems. The waterpower program supports the hydropower industry and complements existing investments by developing and deploying new technologies and key components, as well as by identifying key areas of opportunity from which the generation of hydropower can be improved. In 1878, the world's first hydroelectric plant was used at the Crag side country house in Northumberland, England, to fuel a single lamp. Four years later, in Wisconsin, USA, the first plant to service a system for private and commercial customers was opened, and hundreds of hydropower plants were in operation within a decade (Sims, 1993; and Fridleifsson, 2001).

9.4.1 Challenges faced

No two hydropower projects that are exactly alike have ever been installed, and each power site has its own specific design and construction challenges that need to be faced and solved. However, we can discern those general types of plant layout that are compatible with the general and significant site characteristics, such as head, accessible flow, river topography, etc. They are all interdependent. These characteristics, along with those of the market and the type of load, affect the manner of production, which in turn affects the size of the plant and the number of its units. The general classification may be (1) concentrated fall where the hydropower head is mainly due to the height of the divided fall dam and (2) where the dam serves as a barrier only. It is evident that the development of hydropower is a source of renewable energy and that its renewability is a major advantage. The environmental impact is marginal when hydropower construction happens at existing dam sites (El Haj Assad *et al.*, 2017). However, when an existing dam site is built for power production, essential changes will occur. Water that would usually flow over a spillway, for example, where a significant amount of aeration would occur, is instead funneled into turbines, where little to no aeration occurs. The resulting significant difference in the rate of aeration at a given point in the river can have a significant effect on the dissolved oxygen content of the river's considerable reach. The environmental impact can be substantial in some areas, especially those near large municipalities. Although the fuel costs of hydropower plants are small, the cost of their construction and capital equipment per unit of installed capacity is typically much higher than that of thermal power plants. This can be used either as an asset or a disadvantage. The economic viability of the production of hydropower is very responsive to the difference between a discount rate used to add present value to future profits and costs and an expected escalation rate used to estimate future electricity costs. The discount rate, which is usually fixed, is taken as the load interest rate. An estimate, which can vary greatly, is the escalation rate.

9.4.2 Hydropower—A boon to the economy

A hydroelectric dam, for instance, which is already in operation, looks like a very good investment in a time of escalating inflation. It is also important to look at the overall economy of that area when considering hydropower production within a given region. For example, it should be noted that the

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production of hydropower means that a significantly greater percentage of the investment capital will remain within a given area because local engineers and contractors will do much of the construction work. Specialized companies design and install more advanced coal-fired and nuclear power plants, which also ensures that vast sums of money are left behind by the local economy. The same is true for the amount of capital required for fuel for thermal power plants in many instances. This major drain on the economy can be quite critical. Furthermore, hydropower facilities need limited maintenance and do not have the same criteria as more advanced thermal power plants for professional workers. Among the other advantages of hydropower is that it can also be easily installed in less developed economic regions. The economic climate will rely on many potential possibilities for small hydropower developments. For small turbine technology, there is a definite demand. If this market is to be established, it can be anticipated that substantial changes, both in the operating characteristics of turbines and lower costs, would lead to more cost-effective small hydropower installations (Yüksel, 2007). There are also other facets of tiny hydropower that have not yet been studied.

In several cases, small hydropower stations are the catalyst for the growth of small manufacturing facilities in developing countries. It should also be noted that the present mini-processor technology has evolved to the point that the operation of a system of small hydropower plants on a fully automated basis is feasible, with only a traveling crew of workers necessary for maintenance purposes. In certain situations, the number of small sites that could be built will be capable of providing the same amount of power as a single large nuclear power plant, with no safety or security concerns that are usually associated with large-scale construction. If the total amount of power is spread over many small plants, the overall efficiency will improve, as all plants are very unlikely to experience an outage at the time of the plant failure. However, there are also some drawbacks to the production of small hydropower (Oud, 2002). The fact that economies of scale do not dominate, it results in high initial costs for an installed capacity. These plants are run-of-river in many instances; that is, their capacity to produce power fluctuates wildly with the seasons, preventing a system of small power plants. Peak power is available in late spring in many parts of the world, while peak demand occurs in midsummer or midwinter (Sharma *et al.*, 2013). In addition to the lost economies of scale, other drawbacks are related to technological setup. Low head installations, for example, are those in which the usable head is less than approximately 20 m. Since the available power is proportional to the product of flow and head, in order to produce a specified power level at the lower head, greater flow quantities must be required. The size of the computer is, therefore, rising, causing a disproportionate increase in the cost of the amount of power produced (Kaygusuz, 2002; and Xingang *et al.*, 2012).

9.4.3 Developments of hydropower

For decades, construction of hydroelectric dams has been increasing in developed nations, where millions of residents are still not connected to the electric grid. This also includes megaprojects that replicate the issues found by massive dams constructed by the United States and European countries in the past: destroying river ecology, causing major erosion, destruction of marine and terrestrial habitat,

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releasing large quantities of greenhouse gases, displacing thousands of inhabitants, and impacting food systems and water quality.

The viability of these undertakings is usually not scrutinized enough by those who promoted them. The priority in the building of major dams is to produce electricity for rising factories and urban communities, all of which frequently overshadow socio-economic and environmental concerns. They also do not even have access to electricity because the fuel from the massive dams is not delivered to them, and their disturbed lives are not adequately paid for. Renewable energy is required by all countries, and hydropower should be part of this portfolio. However, sustainable and creative alternatives need to be found that integrate the production of hydropower with other sources of energy, thus creating benefits that outweigh, mitigate, or even remove the negative environmental, behavioral, cultural, and socio-economic externalities arising from big dams (Subramaniam, 2013).

9.5 OPTIMIZATION OF HYDROTHERMAL OPERATING SYSTEMS

The operation of a system with both hydro- and thermal plants, although beneficial, is significantly more complicated because hydropower plants have low operating costs but are limited by the amount of water available for hydropower generation in a particular period of time. As a result, the problem falls within the category of dynamic optimization. The challenge of minimizing the operating cost of a hydrothermal system may be understood as reducing the fuel cost of thermal plants while maintaining water availability (storage and inflow) for hydropower production throughout a specified time of operation.

9.5.1 Hydrothermal energy systems theory

The issues of formulation and solution methods are demonstrated using a simplified hydrothermal system for clarity and comprehension in Scheme 9.1. A fundamental hydrothermal system comprises one hydroplant and one thermal plant that supplies electricity to a centralized load. Real power generation is used as the control variable, and transmission losses are calculated using the loss formula.

9.5.2 Nature of geothermal energy

Geothermal energy is the terrestrial heat produced in saturated pore space, cracks, and cavities deposited in or discharged from rocks and fluids (water, brines) and are commonly used in two ways: for power generation (electricity) and for direct use, e.g., heating, cooling, aquaculture, horticulture, spas, and a number of industrial processes, including drying. Through taking heat from geothermal sources, thermal energy is used replenished with natural refilling. Hydrothermal reservoirs are

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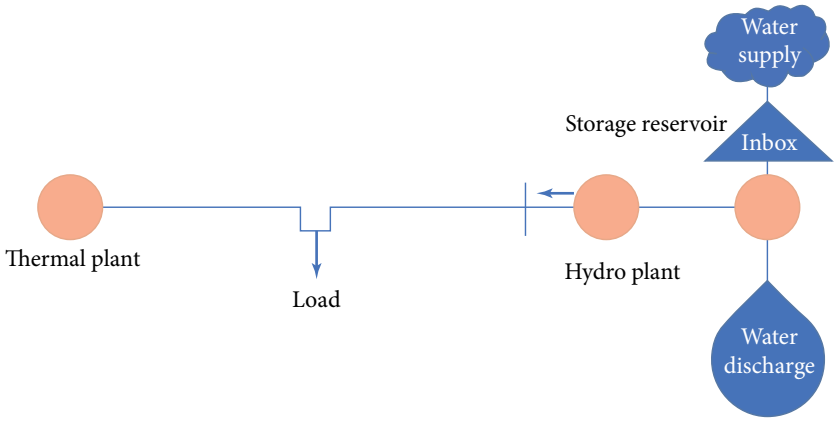

SCHEME 9.1
Fundamental of a hydrothermal power system.

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considered reservoirs that are naturally sufficiently hot and permeable, whereas reservoirs that are sufficiently hot but require artificial increases in rock permeability are called engineered (enhanced) geothermal systems (EGSs). It is possible to use geothermal energy to produce electricity or directly for processes that need thermal energy. Also, it is possible to supply dispatch able, base-load power plants using geothermal energy.

There is a natural power source located below the earth's crust that has been around for centuries. Much below us, underground, there are ponds of water heated by magma (or molten rocks). Our geothermal lakes make up these bodies of water. The essence of geothermal power is to harness the power of the earth's temperatures to power, heat, or cool our homes and companies. According to the Geothermal Energy Organization, there are now geothermal projects in more than 80 countries, and while the United States is currently the world leader in geothermal electricity, other countries, such as Indonesia, Turkey, and Kenya, are also expanding their power capacities (https://www.saveonenergy.com/how-geothermal-energy-works/).

Geothermal energy systems have a modest environmental impact, are not threatened by climate change, and have the ability to become the world's largest energy system. It is the lowest cost source of zero-emission renewable thermal fuel, direct use of base load, and power generation. It can also be anticipated that the transition in more emissive fossil oil sources to geothermal energy would play a key role in climate change mitigation strategies. The usage of ground source heat pumps (GSHPs) of energy derived from earth's temperatures at a shallow depth is a typical method of the use of geothermal energy. At least since the Middle Paleolithic, the direct use of regular flows of geothermally heated water to the surface has been practiced.

The most widely recognized geothermal manifestations of convective heat flow are correlated with strength, hot springs, and geysers (e.g., the movement, including hot water to the surface of the land); volcanoes (e.g., the movement of volcanoes, magma to the surface, and sea floors of the land); and certain types of minerals of economic importance—the deposits arising from their injection recovery are geothermal liquids. Geothermal wells create naturally hot liquids from a continuum of normal high to low permeability and porosity found in hydrothermal reservoirs. With hydraulic fracture stimulation and chemical treatment, the ability of geothermal reservoirs to flow hot fluids can be improved (e.g., acidization) by improved or engineered geothermal processes, producing artificial fluid pathways. The quantity, depth, and diameter of output wells for geothermal energy differ according to local specifications for direct use and for power plants. More thermal energy generation per well benefits from higher temperatures and higher flow speeds. Direct steam (often called dry steam), flash steam, and binary cycles are used by the main types of geothermal power plants (Hood *et al.*, 2012).

9.5.3 Geothermal energy conversion systems

Energy conversion systems must also be selected and always modified to accommodate a given geothermal energy resource. For moderate-to-high temperature liquid-dominated services, single, double, and triple-flash systems are used, dry-steam plants can be used for the special dry-steam resources, and binary plants utilize liquid-dominated resources at lower temperatures (Das *et al.*, 2020).

There are several geothermal resources that involve more complex systems of energy conversion than the simple ones. In addition, by combining various types of power plants into a single, dynamic organization, energy conversion technologies have developed to address the needs of particular emerging fields. By enhancing the quality of resources used, many of these have already attained commercial status. Others are at varying stages of growth but promises to fulfill potential demands for geothermal resources (Sun *et al.*, 2018a).

1. Integrated single- and double-flash plants: The addition of one more flash using the divided brine theoretically makes for a lower pressure unit for conversion of geo-thermal energy as the geofluid reservoir temperature is around 220–240 °C. However, a single-flash system is still installed in those cases and yet has been running successfully for quite some time. The arrangement is shown in Fig. 9.1.
   The benefit of this arrangement is that it is not required to drill any new wells to supply the machine with an additional resource.
2. Combined single- and double-flash plants: If the resource temperature is equal to or greater than 240 °C, the single-flash units may be increased with a true double-flash bottoming period. In this scenario, two extra flashes are exposed to the waste brine from the first units, resulting in two additional low-pressure steam flows. It may be argued that this forms a triple-flash if the number of flashes encountered by the geofluid is literally counted, but the use of the phrase "combined single- and double-flash" seems reasonable considering the sequential timing of the creation of the devices.

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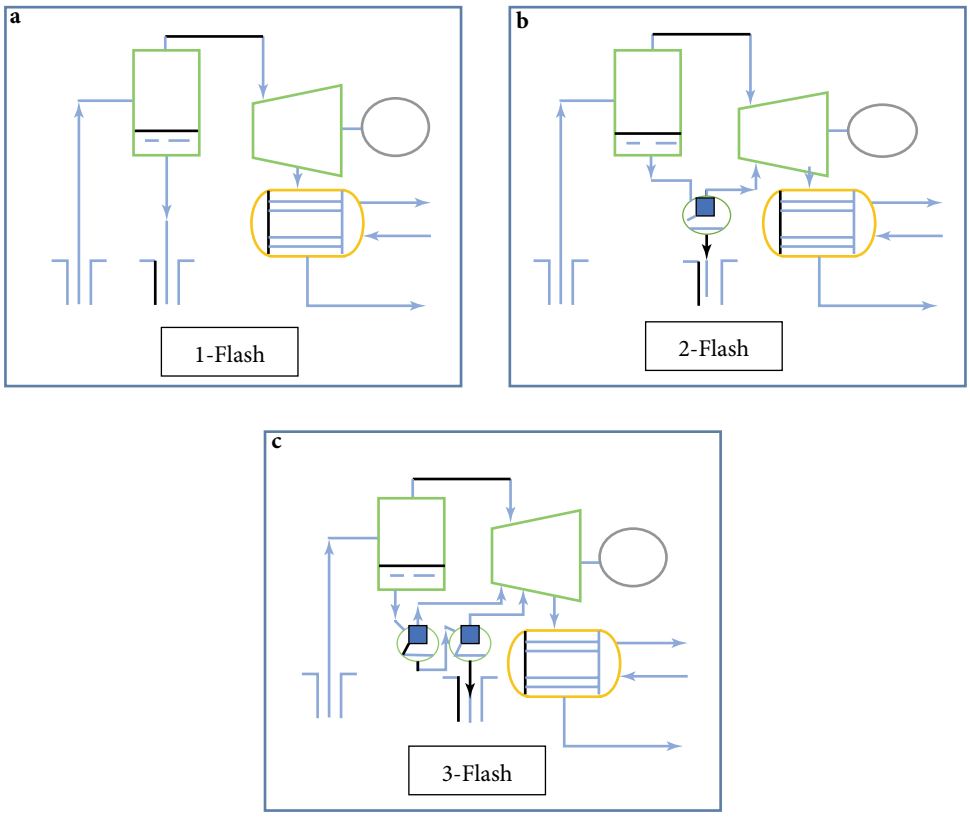

FIG. 9.1
Representation of a basic geothermal energy conversion system: (a) 1-Flash. (b) 2-Flash. (c) 3-Flash. Reproduced with permission from DiPippo, *Advanced Geothermal Energy Conversion Systems* (Elsevier, 2016). Copyright 2016 Elsevier Books.

While the thermodynamics of this arrangement is favorable, there could be issues with chemical scaling due to silica deposition at the low temperatures associated with the last flash, with better resource consumption performance than with the initial single-flash factory. This arrangement is shown in Fig. 9.2. It has been a safe option because there is no chance of deposition of silica or the owner of the plant is able to invest in low-temperature brine chemical treatment to avoid or regulate the development of scales (Feng *et al.*, 2020).

The idea of a total flow system derives from the desire to escape the irreversibility associated with the flickering processes necessary by a single- or double-flashing plant. The separation process often needs large pressure vessels and separate exit pipes for steam and water, while not necessarily lossy, both of which contribute to the plant's capital expense. Important savings would be accomplished

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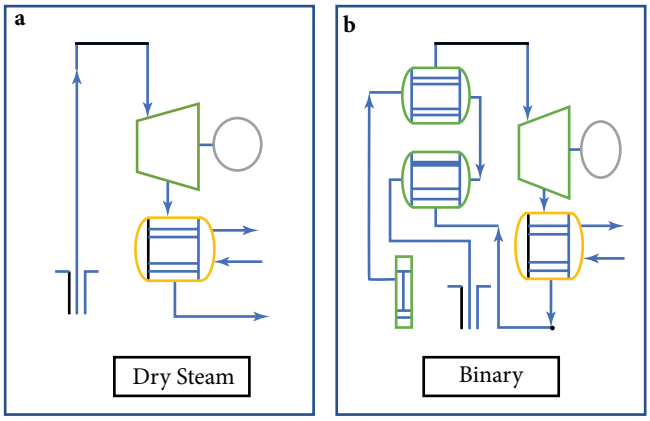

FIG. 9.2
Representation of a basic geothermal energy conversion system: (a) Dry steam and (b) binary. Reproduced with permission from DiPippo, *Advanced Geothermal Energy Conversion Systems* (Elsevier, 2016). Copyright 2016 Elsevier Books.

if a way could be devised to use the geofluid directly when it rises from the well in the prime mover, be it a turbine or some other specifically built unit. Three main research attempts aimed at creating such a device have been made. A single-stage pure impulse turbine was involved, another used a positive displacement expander (PDE) (a helical screw expander), and a new design of a rotary separator turbine was the last (RST). In the late 1970s, the first was a U.S. Department of Energy initiative and the other two were private projects, both of which obtained funds from the government and other business groups (DiPippo, 2016).

9.5.4 Geothermal power plants

Mainly, geothermal power plants come in two classes, namely, cycles of steam and binary power. These loops work at high levels of geothermal fluid enthalpy. Just one throttling valve (expansion valve) by which the geothermal fluid is extended is used in the single-flash loop and one separator to isolate the vapor from the liquid during the expansion step in the expansion valve. At constant pressure and temperature, this distinction happens. To produce electricity, the vapor generated is sent to a steam turbine while the liquid is produced. The temperature of geothermal fluid for the flash steam power plants in the well is over 182 °C. In order to condense the steam escaping the engine, flash steam power plants use a condenser and then re-inject it into the atmosphere.

Binary cycles (ORC) are normally applied when the geothermal fluid has low enthalpy, but ORC can run at temperatures of up to 200 °C with modern chemical technologies that enables the production of new mixtures of working fluids. The advantage of such a power plant is that in a closed loop, the geothermal fluid is pumped such that no damage to the atmosphere is generated. This cycle, however, involves a secondary fluid that is heated in the heat exchanger (vaporizer) by the geothermal fluid, where it gradually vaporizes and is then sent to the turbine for electricity generation (El Haj Assad *et al.*, 2017).

9.6 SINGLE-FLASH STEAM POWER PLANT

Due to the poor steam content that emanates from the two-phase fluid after the expansion valve, the use of a flash system results in the removal of a significant portion of energy in brine (liquid) from the separator. For geothermal energy accessible at temperatures above 190 °C, single-flash power

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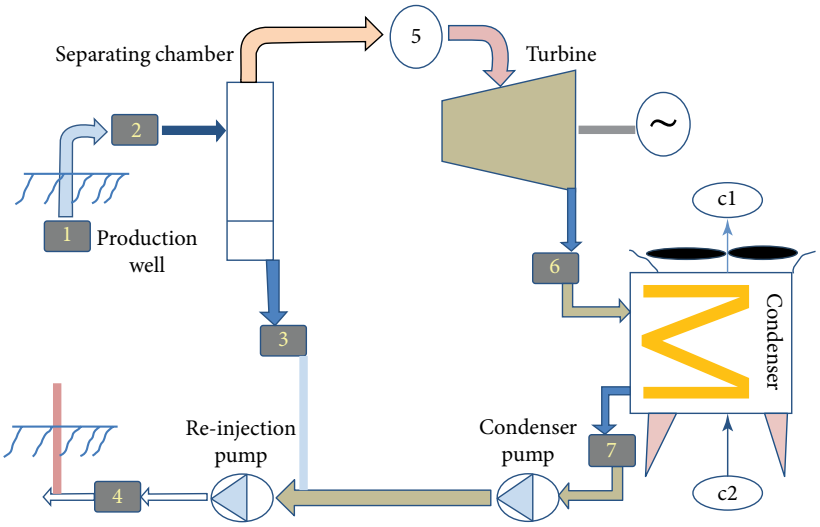

FIG. 9.3
Single-flash power plant (El Haj Assad *et al.*, 2017).

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plants are commonly regarded to be the most economical option. For normal pressure environments, higher temperature energy can create more liquid and steam. In the case of resources that have high temperatures where two phases are dominated, the geothermal fluid goes to the surface of the borehole as a mixture of steam and liquid (brine).

Single-flash power plants are categorized according to their types of steam turbines, i.e., the escape conditions of the turbines (Fig. 9.3). The single-flash with a condensation system and the single-flash back pressure system are the two fundamental forms of the first type to condensate the steam, leaving the steam turbine. A condenser running at a very low pressure is required in this case. To sustain a significant variation in enthalpy throughout the expansion phase of the steam turbine, the condenser can work at low vacuum pressure, resulting in a higher power output.

1. Dual flash steam power plant: Based upon the requirements of the resource, the dual flash steam plant (double flash) is often favored over the single-flash steam power plant. In fact, it generates more steam due to the use of two separators; however, rest of the features are like a single-flash power plant. The use of two separators results in the use of a two-stage steam turbine, with one stage running at high pressure and the other one operating at low pressure. As their power generation capacity is in the range of 4.7–110 MW, dual flash power plants can produce up to 15%–25% more power than a single-flash power plant. In a dual flash power plant, the saturated liquid leaving

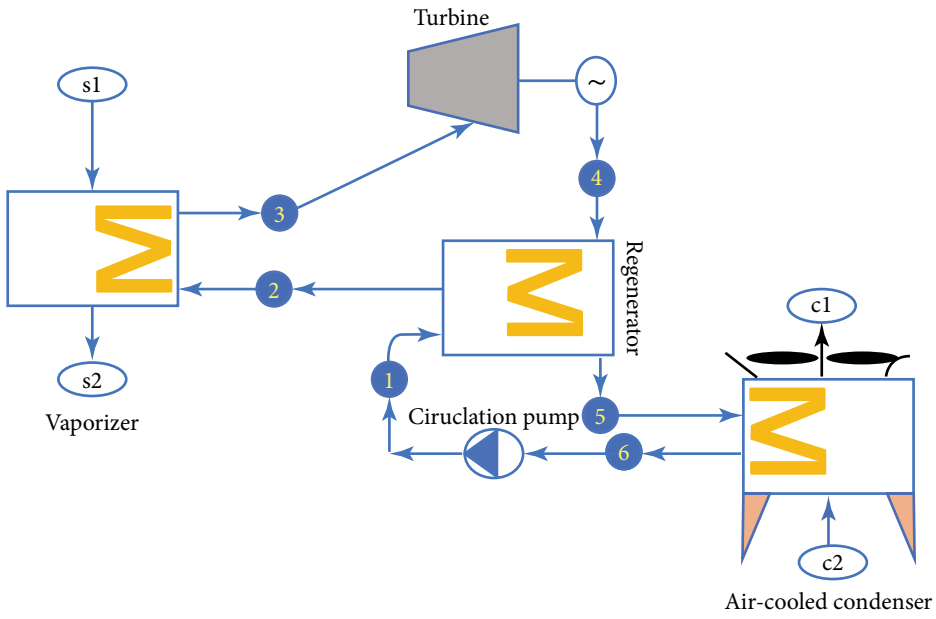

FIG. 9.4
Dual flash power plant (El Haj Assad *et al.*, 2017).

the first separator is directed to the second separator at lower pressure, resulting in more steam production (Fig. 9.4).

Each steam is guided to a steam turbine using different pipelines after steam output at high and low pressures. A steam turbine may be a dual inlet turbine, a single turbine, or may consist of two separate tandem compound turbines working based on the pressure of the steam inlet. The dual flash power plant components are identical to those of a single-flash steam power plant. Depending on how the dual flash is made, the mineral content of the water becomes concentrated; thus, an initial study on resource specification is of outmost importance for smooth design and running of the plant.

2. Binary power plants: In this type of power plant, to operate the ORC turbine, a secondary fluid such as hydrocarbon or fluorocarbon is used instead of water. In ORC, the geothermal fluid is circulated and sent back to the re-injection well in a vaporizer. In the vaporizer, the secondary fluid is heated and vaporized by the interaction of heat between the geothermal fluid and the secondary fluid. The created vapor is guided to the turbine from the secondary fluid for the generation of electricity. The vapor exiting the turbine travels into a regenerator where the superheated steam is used until it reaches the vaporizer to heat the concentrated fluid leaving the condenser (Fig. 9.5).

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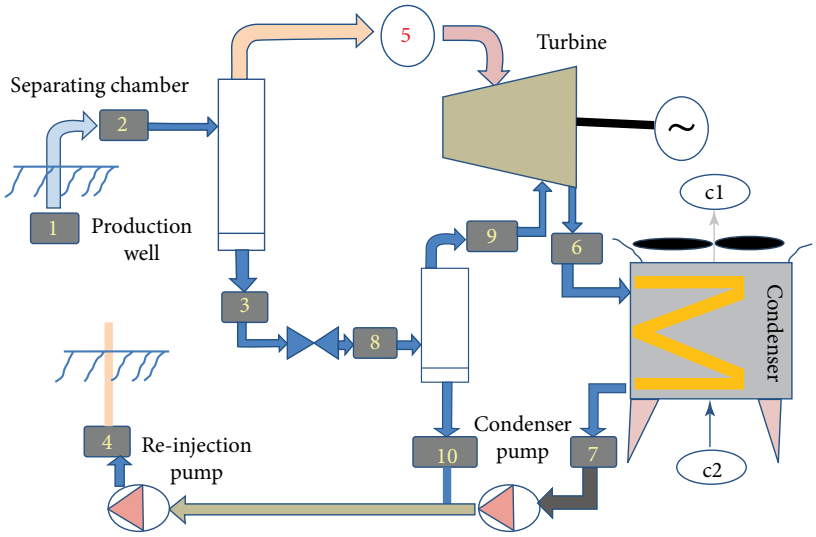

FIG. 9.5
Binary power plant (El Haj Assad *et al.*, 2017).

The key benefits of ORC are that it runs at a low temperature that results in low mechanical pressures on the turbine, along with the fact that during the vapor growth in the turbine, there is no corrosion of the turbine blades due to the lack of moisture. In addition, the turbine in ORC has a smaller capacity because it is also less inefficient, and there are no issues with air in-leakage or problems related to vacuum operation; therefore, vacuum is not needed.

9.6.1 Application of geothermal energy

Two forms of geothermal energy can be distinguished depending on the depth of the borehole.

1. Near-surface geothermal energy: It can be found up to the depth of 400 m, which can be used for heat and cold production.
2. Deep geothermal energy: After the range of near-surface geothermal energy, after 400 m, deep geothermal energy can be found. It can be used for heating purposes and for electricity generation.

9.6.2 Near-surface geothermal energy

Geothermal energy from depths of up to 400 m and temperatures of roughly 25 °C is utilized to heat and cool buildings and plants in geothermal energy applications. The heat energy from these depths is normally not used directly due to the still relatively low temperature but is instead elevated to

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the desired temperature level using heat pumps. The same geothermal energy system that heats the building in the winter may also cool it in the summer. As a result, the subsurface may be used directly as a source for climatic conditions, saving money on air-conditioning system chilling.

Near-surface geothermal energy has already shown to be a cost-effective and environmentally benign alternative to fossil fuels for single and multi-family homes. Earth collectors, geothermal heat exchangers, groundwater fountains, and geothermal heat probes are examples of near-surface geothermal energy systems.

9.6.3 Deep geothermal energy

The usage of geothermal energy in other dimensions is challenged by deep geothermal energy. At a depth of 400 m and lower, deep geothermal energy can be found. Not only are warmer springs unearthed at higher depths, but boreholes up to 7 km deep are also sunk. The systems that run on them are likewise bigger and more powerful. Heating networks are fed, and the entire city areas are heated with geothermal energy from deep geothermal sources. A geothermal power plant may also create energy if the temperature is high enough. Baths can, of course, be filled with hot thermal water as well. Geothermal energy is not affected by the weather and can provide heat and power practically constantly all year.

The uses of deep geothermal energy can be listed as follows:

1. Supply of heat: Large public, commercial, and industrial structures, as well as bigger communities and regions, require local and long-distance heating. However, it is also used to heat greenhouses where vegetables are grown.
2. Generation of power: Geothermally produced electricity is accessible 24 h a day and might be utilized as a power supply's base load. Deep geothermal energy is used to create electricity in cogeneration of heat and power for efficiency reasons.
3. Balneological use: In thermal baths, heated water is used (https://www.mse.tum.de/en/gab/what-is-geothermal-energy/applications-of-geothermal-energy/).

9.6.4 Largest geothermal power plants

1. The tenth largest geothermal plant in the world is built in Garut, Indonesia's Pasirwangi District. It is made up of three different plants that were constructed between 1994 and 2007. This facility has a capacity of 259 MW, producing almost 50% more power than Niagara Falls' Sir Adam Beck pump generating hydroelectric station. Indonesia's volcanic geology is highly active, and geothermal energy is becoming increasingly popular across the country.
2. The ninth-largest plant is also in Indonesia, in the West Java region. It was planned and built by Aecom, Sumitomo Corporation, and Fuji Electric and is managed by a Star Energy subsidiary. It has a 227 MW production capacity and covers a wider area than the Darajat station. The geothermal field at WyangWindu is 40 km^2 in size.

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3. The eighth largest plant was built in Philippines with a capacity of 232.5 MW. The Electricity Development Corporation owns this facility, which provides energy to Luzon Island. It has been in operation since 1999 and is projected to last at least another 30 years. Hot springs abound in Iceland, and many residences outside of Reykjavik have secondary, private geothermal generators.
4. The seventh biggest geothermal plant in the world is located on Iceland's Hengill volcano, with a production capacity of 400 MW thermal energy and 303 MW electric energy. This huge geothermal plant in southern California is made up of ten geothermal units grouped together.
5. This set of plants is the world's sixth largest geothermal energy generator, with a combined output of 340 MW. The Makban Geothermal Power Complex is the world's fourth biggest geothermal plant, with a capacity of 458 MW. This complex is made up of six factories that are spread over Laguna and Batangas provinces.

Moreover, the Philippines has a great geothermal infrastructure, but to achieve 100% sustainability, it would need to expand geothermal production to a greater extent. With a capacity of 720 MW, the Cerro Prieto Geothermal Power Plant in Northern Mexico is the world's third biggest in capacity. The Comisión Federal de Electricidad owns this facility, as does every other power plant in Mexico. The facility is built on a geological feature that is rather peculiar, namely, a spreading fault line in a landlocked location. Normally, the phenomena can only be detected on the ocean floor. The enormous Larderello Complex, which consists of 34 units, is the world's second biggest geothermal plant. This geothermal facility has a net capacity of 769 MW. The original plant, which is the oldest of its kind, was built in 1913. This massive complex, about 100 km north of San Francisco, California, made up of 18 power units with a total operating capacity of 900 MW, is the world's largest geothermal plant installed and commissioned until today. It is massive, covers 45 square miles and produces enough energy to power almost 1×10^6 households (https://www.mse.tum.de/en/gab/what-is-geothermal-energy/applications-of-geothermal-energy/; www.climatecare.com/blog/the-worlds-10-biggest-geothermal-energy-plants/).

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9.7 CONCLUSIONS

In this chapter, we have discussed about the nature of hydro- and geothermal energies along with necessary details on plant design and energy conversion and the latest world scenario of their application. It would surely help to conceptualize the readers about these important clean energies and would aid to evolve new ideas for further growth in both technological and energy management fronts.

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CHAPTER

10 INFORMATION AND COMMUNICATIONS TECHNOLOGY AND RENEWABLE ENERGY MONITORING

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10.1 INTRODUCTION

Information and Communication Technology (ICT) devices and services have deeply changed the way in which humans work, travel, play, and interact in the last few decades. An increasing number of people earn their living working in front of a computer, and many industrial and agricultural processes have in some way become controlled or monitored by intelligent electronic devices. Many cars are now equipped with a Global Positioning System (GPS) device for easier navigation on unfamiliar roads and time-of-arrival estimation, even taking into account traffic jams and road works. Entertainment has a rising digital footprint in the form of video games, online games, and in-house intelligent workout devices. The steep rise of online social services, such as Facebook [over 1×10^9 users near the end of 2012 (Van Heddeghem *et al.*, 2014)], and the continued proliferation of mobile phones show that inter-human communication and interaction are increasingly taking place via digital platforms. In 2018, there were 3.6×10^9 Internet users, this number is expected to increase to 5×10^9 users by 2025 and the number of Internet connected devices is expected to double from 12×10^9 in 2019 to 25×10^9 by 2025 (IEA, 2020), and this growth trend is expected to continue worldwide.

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This growth has led to concerns that the tech sector industry will consume an increasing share of electricity, which has an associated growing impact on the environment. This impact comes in many forms and is often expressed as a "footprint," energy footprint, and CO_2 emission footprint, which are the most popular and widely used measures. The carbon footprint is also an important component of the ecological footprint.

However, the ICT is more than just an emerging energy consumer, and it is currently reshaping the economic production process as well as residential life across the globe.

In this chapter, we will be looking at this vital sector and its role in transforming our life into a new modern digitally based lifestyle, its global impact on energy consumption, and the environment. We also look at ways that RE helps to expand services of this sector worldwide and reduce the impact of this sector on the environment by utilizing green renewable energy to power it.

10.2 WHAT IS ICT?

The term ICT is understood to cover computer and peripheral equipment, including local area networks, telecommunication equipment and networks, and data centers. It refers to technologies that provide access to information through telecommunications. This includes the Internet, wireless networks, cell phones, and other communication mediums. ICT consists of hardware, software, networks, and media for the purposes of processing, transmission, storage, and presentation of information.

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10.2.1 ICT in our life

There is no doubt that the IT revolution has enhanced quality of life, from improving health care, to transforming education and simplifying learning and information processing for children to introducing new business concepts such as e-commerce and giving consumers more convenience in their interactions with business and government and making it easier to measure environmental quality. However, while these and other benefits are important, perhaps the most important benefit of the ICT revolution is its impact on economic growth. The diffusion of information technology and telecommunications hardware, software, and services turn out to be a powerful driver of growth, having an impact on worker productivity three to five times that of non-IT capital (e.g., buildings and machines). Moreover, there are strong indications that IT has the potential to continue driving growth for the foreseeable future.

10.2.2 Future of ICT and impact from COVID-19 pandemic

The COVID-19 pandemic that hit the world at the end of 2019 and during 2020 has given us yet another evidence about the importance of the ICT sector and how far it has been interlacing with our daily life activities and it could interact.

When social distancing rules were applied due to the pandemic, companies sent their employees to work from home and people communicated via online conferences or by chat and email; pupils and students were asked to stay and learn from home; and most businesses were turned to online service to continue in the market. Never before had so many people been simultaneously working from their home offices, yet, for the most part, the technology coped. This rapid change toward digitalization and the massive shift to telework recently fuelled by strict public safety rules due to the pandemic are driving the demand for ICT further.

Teleconference and meetings tools, such as Zoom and Google meet, have become very popular. Indeed, the share prices of ICT companies such as Zoom surged significantly in early February 2020, and throughout the year amidst the growing inclination of the increasing number of companies emphasizing on reducing the business travel and shifting to online services offered by these collaboration services providers.

This growth, therefore, requires more reliable and sustainable energy for effective operation. In particular, some recent developments in ICT have involved booming energy demand and potentially hinder global energy sustainability. For example, cloud computing, as the interaction between telecommunications technology and a data center, transfers massive data between devices and data centers and consumes a large amount of energy (Salahuddin and Alam, 2016).

Like all sectors in economy, business, and industry, the ICT sector will have to do its part to address global climate change and reduce its own environmental footprint, with the ultimate goal of achieving net-zero emissions.

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10.3 ICT ENERGY CONSUMPTION AND ATTEMPTS TO SAVE IT

The power consumption in the ICT sector is growing continuously and is in line with the exponential data traffic increase. A study in 2017 (Anders, 2017) about ICT power consumption over the 5-year period of 2007–2012 found that the combined electricity consumption of communication networks, personal computers, and data centers is growing at a rate of nearly 7% per year (i.e., doubling every 10 years).

The energy consumption by the ICT sector has been under scrutiny recently, and it stimulated a stream of articles and studies, many claiming that ICT energy use was exploding and would spiral out of control when the Internet of Things (IoT) becomes a reality and a new global middle class comes online.

To accurately quantify the power consumption by ICT, one must look at the power consumption in the different systems equipment and devices in this service, e.g., data centers, networks servers, with their accompanying influx of a variety of mobile telephony facilities, devices, and gadgets such as smartphone, mobile TV, etc., which function ubiquitously.

The number of data centers and cellular sites and their related devices rose fast in recent years, thus making the telecommunication and ICT industry grow very fast. To estimate the power consumed in all devices and equipment that produce, store, transport, process, and display Zettabyte (extremely large number) of data, we must look for the energy used by data centers that have become the backbone for Internet growth and by devices, ubiquitous broadband wired and wireless communication networks, and countless end-use devices from PCs to tablets smartphones to smart TV in addition to manufacturing facilities that produce all the ICT hardware.

Different studies present different results and estimate the ICT power consumption, depending on the size of the study, the entirety of the investigation, and the geographical location of the study in concern. However, the sector's share of electricity is non-trivial, which is challenging for governments because ICT pervades all fields of our economy, so it is very hard to attribute consumption accurately or implement effective policy measures.

In 2012, more than 200 GW annual average power consumption in the information and communications technologies (ICT) industry was monitored, one quarter of which are from telecoms infrastructure and devices (Van Heddeghem *et al.*, 2014). In an update to a 2016 peer-reviewed study, researchers found that without dramatic increases in efficiency, the ICT industry could use 20% of all electricity and emit up to 5.5% of the world's carbon emissions by 2025 (The Guardian, 2021).

According to the International Energy Agency (IEA) report in 2020, data communication networks consumed about 250 TWh in 2019, about 1% of global electricity generation. As the demand for data increases higher rate than near term efficiency improvements, data communication networks' electricity consumption is expected to rise to 270 TWh in 2022 (International Energy Agency, 2020).

Recently published studies found that ICT is responsible for about 4% of global electricity demand and 1.4% of global Greenhouse Gas (GHG) emissions (Malmodin and Lundén, 2018). A comprehensive study by Andrae and Edler (2015) about electricity consumption by ICT and its growth globally considered three scenarios: worse, expected, and best-case scenarios. Results show that electricity demand from ICT is growing at a considerable rate as shown in Fig. 10.1 for the scenarios between 2010 and 2030.

Figure 10.2 shows the share of ICT sectors, depending on the scenario: in 2010, it is 8%–14%, in 2020, it is 6%–21%, and in 2030, it is 8%–51%.

10.4 RENEWABLE ENERGY AND ICT

10.4.1 Renewable energy resources (RERs)

RERs, such as light, vibration, biogas, biofuel, heat, radio frequency (RF), and wind, are abundant energy resources in the natural environment around us. Renewable energy can be obtained from sunlight,

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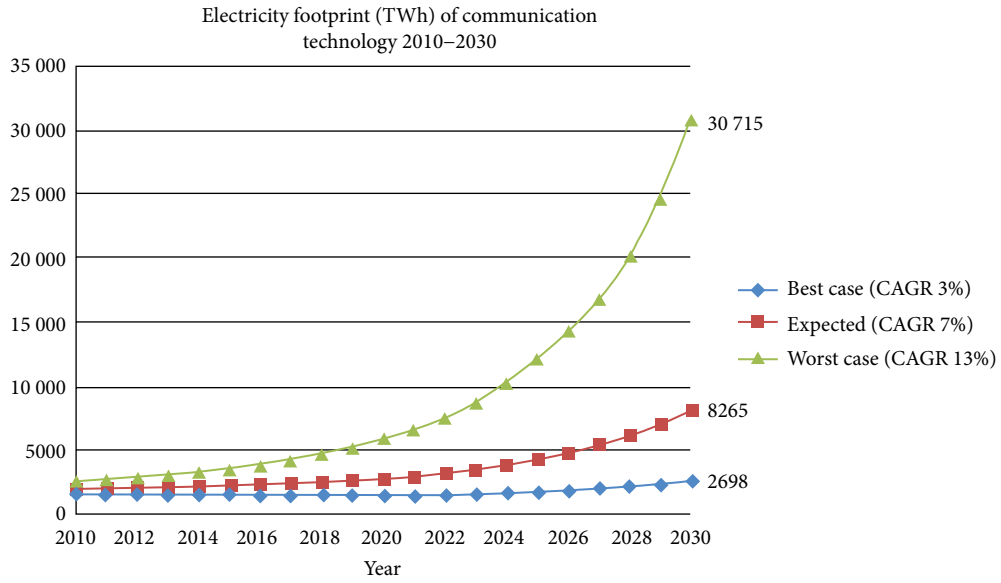

FIG. 10.1
Global electricity demand of information communication technology, 2010–2030 (Andrae and Edler, 2015).

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which can be captured in large scale solar farms or from artificial light (e.g., indoor environments in homes or office buildings). Photovoltaic systems use cells to convert sunlight (solar energy) to electricity; however, solar energy is seasonal and its availability depends on the geographic location. Another form of renewable energy is wind, and it is a clean renewable energy source, which is free and readily available. Wind turbines are used to capture wind power and convert it to electricity in wind farms.

RER could be found distributed all over the world. Deserts can provide solar energy on an enormous scale, while coasts offer huge potential for wind energy. On the other hand, great geothermal energy resources are located along the circum-Pacific "Ring of Fire," while countries that have mountainous terrain present high potential for hydropower due to rainfall gathering capability. On the other hand, bioenergy is available in subtropical regions.

Energy generated from renewable sources does not produce greenhouse gases such as CO_2 and is considered for clean electricity generation for telecommunication and ICT industry because of its sustainability, reliability, and availability as being a domestic source of energy, harnessing a limitless local resource, and is competitive to other forms of energy generation.

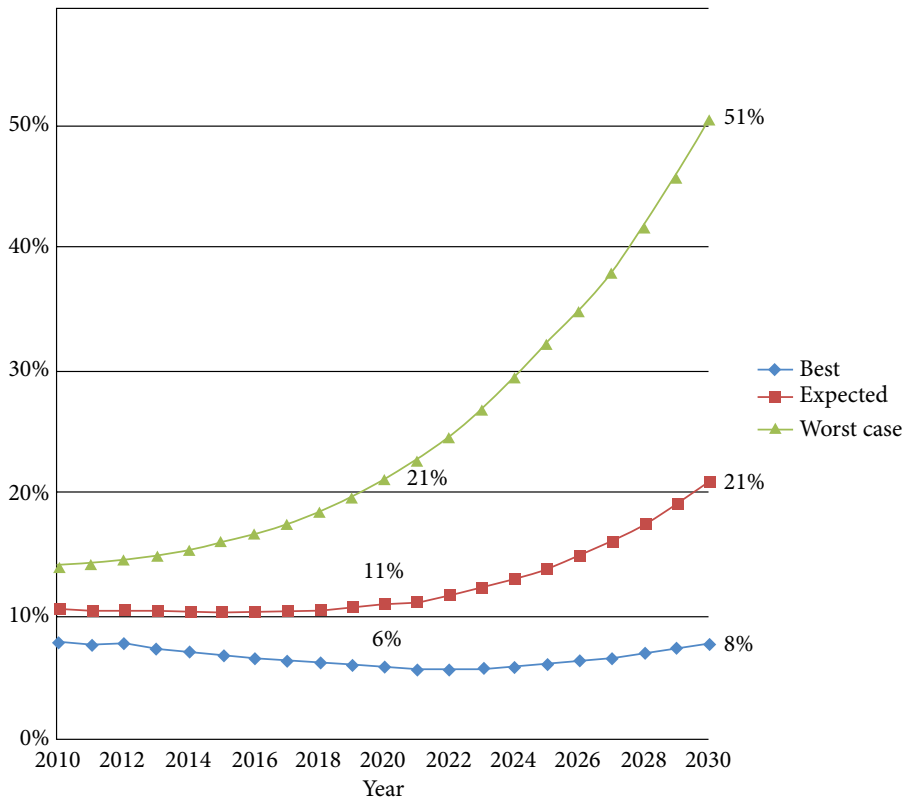

FIG. 10.2
Share of communication technology of global electricity usage, 2010–2030 (Andrae and Edler, 2015).

According to IEA, in 2009, renewable power was ≈20% of global electricity usage or ≈4000 TWh (International Energy Agency, 2010). Then, it is assumed that renewable electricity is set to globally grow at an annual rate of 5% between 2010 and 2030 (Andrae and Edler, 2015). The approximate amount of total electricity usage and the amount produced from renewable sources between 2010 and 2030 are shown in Fig. 10.3.

10.5 IMPORTANCE OF RE IN ICT PROVISION

RE is important in ICT in two ways. First is the provision of energy in a rural area, as ICT has been recognized as an effective tool for rural development. RE is particularly important in extending the ICT services to rural and underdeveloped areas.

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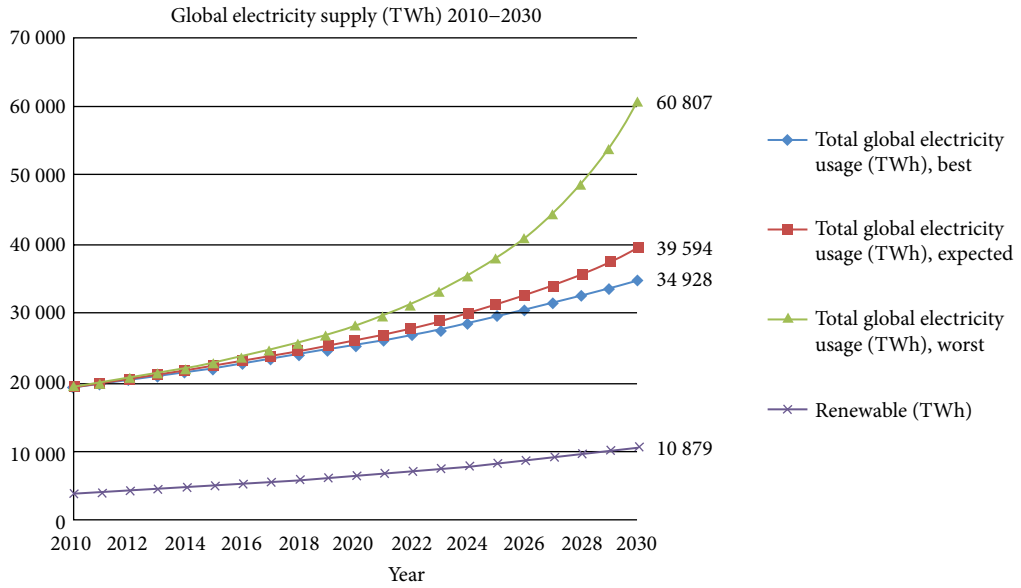

FIG. 10.3
Global electricity supply and the amount produced from renewable sources between 2010 and 2030 (Andrae and Edler, 2015).

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Second, RE helps reduce operational costs for ICT services; as it helps reduce dependency on the classical electricity grid, it would also reduce energy footprint and CO_2 emission and at the same time meet ICT increased demand for energy as it grows fast.

10.5.1 RE support ICT provision in rural areas

The potential of RETs to power rural development has been understood for many decades. In September 2000, the connection between clean sources of energy and rural energy access was explicitly made in the form of the United Nations General Assembly's commitment to a global partnership to achieve a series of eight goals and targets known as the Millennium Development Goals (MDGs) by the year 2015 (UNCTAD, 2010).

The main problems in rural areas are electricity, communication, transportation, and lack of knowledge about new technology. Infrastructural development, in general, has been hindering telecommunication and ICT development in many developing countries.

The introduction of ICT and telecom in rural areas in the Third World has a great impact on improving the lifestyle and social and economic aspects in these areas. ICT can provide information, news, and

knowledge to users that will give meaningful and useful information to be used for both economic and social development. It also provides enhanced communication ability through connecting others beyond the limit by providing enough and advanced communication infrastructure such as Internet networks; however, as these areas are normally in shortage of power, it would be a challenge to deploy ICT networks in these areas.

It is estimated that 2.6×10^9 people in the world lived in villages with no reliable electricity source—or no electricity at all—in 2012; this number has dropped to 1×10^9 in 2020 (IAE, 2020). Extending ICT services to semi-urban and rural areas that have a considerable percentage of the population living in them and where telecommunication infrastructures are not available is bound to have financial implications for both the customers and the operators. Currently, the service in these areas depends on off-grid power by providing energy to ICT equipment on the site by diesel generator (DG) service. The operators will require extra funds to be able to undertake any extensions and installations to connect these areas to the national grid, while the customers will be very sensitive to pricing due to their low-income levels (Tsivor, 2011). Hence, renewable energy has emerged as a prominent and excellent solution for such a scenario.

It has become possible for communities without access to electricity to enjoy the broad benefits of telecommunication networks thanks to the use of renewable energy sources such as solar and wind-based power, combined with more energy-efficient equipment and networks (Stallo *et al.*, 2010).

Distributed electricity generators that capitalize on green RE sources, e.g., solar energy and wind energy, can substantially reduce carbon footprints. Taking advantage of distributed electricity generators, telecommunication equipment manufacturers, such as Nokia Siemens and Ericsson, have designed and built green energy powered off-grid base stations (BSs) to reduce the Operational Expenses (OPEX) of mobile networks in rural areas (Han and Ansari, 2014).

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10.5.2 Renewable energy to meet increased energy demand for ICT

The increase in ICT equipment has an associated growing demand for energy as well as an impact on our environment. Energy supplies for ICT are traditionally provided from on-grid sources (i.e., from a utility provider), as an increase in the energy prices coming from this source in addition to the environmental effect has let operators think of alternative energy supplies that are off-grid. In this section, we look at the utilization of RE in different components in Telecommunication and ICT technologies and services.

10.5.2.1 Cellular mobile networks

It is estimated that there are 3×10^9 Mobile Terminals (MTs) and 3×10^6 BSs worldwide (Ismail *et al.*, 2015). Due to the increasing demands for services and applications, such as audio/video

streaming, VoIP, and social media applications, offered by wireless communication, the use of MTs and consequently the deployment of BSs will further increase. Mobile networks require energy to operate, and this energy is provided by the traditional electrical grid, which is generally powered by fossil fuels (Rehmani *et al.*, 2018).

BSs are the main elements of mobile networks and account for the major energy consumption of a mobile network. They consist of multiple components such as antennas, power amplifiers, radio frequency transceivers, baseband processing units, power supply units, and cooling units.

According to the study by Ismail *et al.* (2015), the total power consumption of MTs and BSs is 0.2–0.4 GW and 4.5 GW, respectively. This high energy consumption contributes to approximately 2% of the total CO_2 emissions worldwide, and this percentage is expected to increase as the number of MTs and BSs continues to increase.

Both the OPEX and the CO_2 emissions can be significantly reduced worldwide when multiple RERs are used by the telecommunication service providers to power their BSs (Farooq *et al.*, 2017).

The potential benefits of renewable energy sources have inspired telecom operators to increasingly install cellular BSs powered by RES that are available locally. There are two types of BSs with regard to the energy used to power them: the mixture of RE BS and grid powered BS.

A RE BS is defined as a BS that has green power supplies from either stand-alone RE power generators or green power farms. A grid powered BS is defined as the BS without any RE power supply.

Despite the potential benefits, the use of renewable energy in the telecom industry may cause a shortage or outage of energy that may arise due to the intermittency nature of RES and its dependency on the condition of weather. The shortage or outage of energy is not allowed in the telecom and ICT as this may affect a large number of sectors in business and economy and cripple the continuity of their services.

However, to ensure the reliability of the supply system that is based on renewable energy, the following ways could be adopted: (i) by integrating the renewable energy sources with the non-renewable energy source, (ii) by integrating different types of renewable energy sources, and (iii) by integrating the renewable energy source or sources with the adequate energy storage devices.

This has led to what is known as the OFF-GRID GREEN MOBILE NETWORKS mode of operation, in which MN is powered by a stand-alone RE power generator. In this operation mode, the RE power generated in the BS is not shared with other BSs, and this is normally used to expand ICT in rural areas.

This has also led to the second operation mode: on-grid green mobile networks that refer to the mobile networks whose BSs are not only connected to the power grid but also equipped with stand-alone RE power generators.

Nowadays, a combination of different renewable energy sources or non-renewable energy sources with renewable energy sources such as a solar PV system with a diesel generator (DG) system has been in

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use by mobile networks operators around the world to bring stability to their networks and expand their services.

In Africa and the Middle East, Huawei technology has installed a diesel generator focused hybrid system to power the off-grid cellular network (Huawei, 2020). The single renewable energy source related problems can be resolved by combining more than one type of RE source such as the integration of DG with the solar PV system.

The combined utilization of different renewable energy sources such as solar PV with wind turbines with a biomass generator-based supply system has been recommended by many researchers in the past as presented by Jahid and Hossain (2017) and Hossain *et al.* (2020).

To provide green power to the mobile base stations of off-grid areas, Ericsson has developed a hybrid supply system based on wind energy (IEEE P2030, 2010). Nokia Siemens has also established a hybrid solar PV and wind energy focused cellular base stations in the urban areas of Germany (E-plus, 2011).

A program called "Green Power for Mobile" has been launched by the GSM Association (GSMA) to aid the mobile telecommunications industry to deploy various RE sources for powering 640 000 new and existing off-grid BSs (Hassan *et al.*, 2013).

When mobile networks support both green BSs and grid powered BSs, the optimization of such networks is about minimizing the on-grid power consumption and maximizing the utilization of green energy.

Due to the unreliability of RE sources and to help BSs, making decision about the optimum energy source used at a time an energy control unit (ECU) (or alternatively—power control unit) has been proposed as an essential unit for managing the changes in energy generation and consumption (Hassan *et al.*, 2013). In case the RE cannot satisfy the energy demand of the BS, the control unit will compensate for the needed energy from the backup storage (or the power grid if such a connection exists). In the case of excess RE, the control unit will use it to recharge the batteries. Moreover, with help of the ECU, a BS can take into account the source of the energy provided by the grid and change its behavior accordingly, e.g., adjust the available throughput as a function of the locally generated wind energy, these BSs are known as "Renewable Energy aware Base Stations."

Mobile and telecom service providers can reduce their grid power consumption by integrating green renewable energy into their networks, hence reducing their GHG emissions and environmental impacts. However, this measure encounters extra cost as it requires providing BS with RE energy systems, and this would add to the capital expenditures (CAPEX) that are determined by the size of the RE energy system, the battery capacity, and other installation costs. Naturally, it is desired to reduce the CAPEX on provisioning green RE energy for mobile networks.

As shown in Fig. 10.4, the optimization of mobile networks that support green energy involves optimizing the utilization level of green energy from both stand-alone power generators and green

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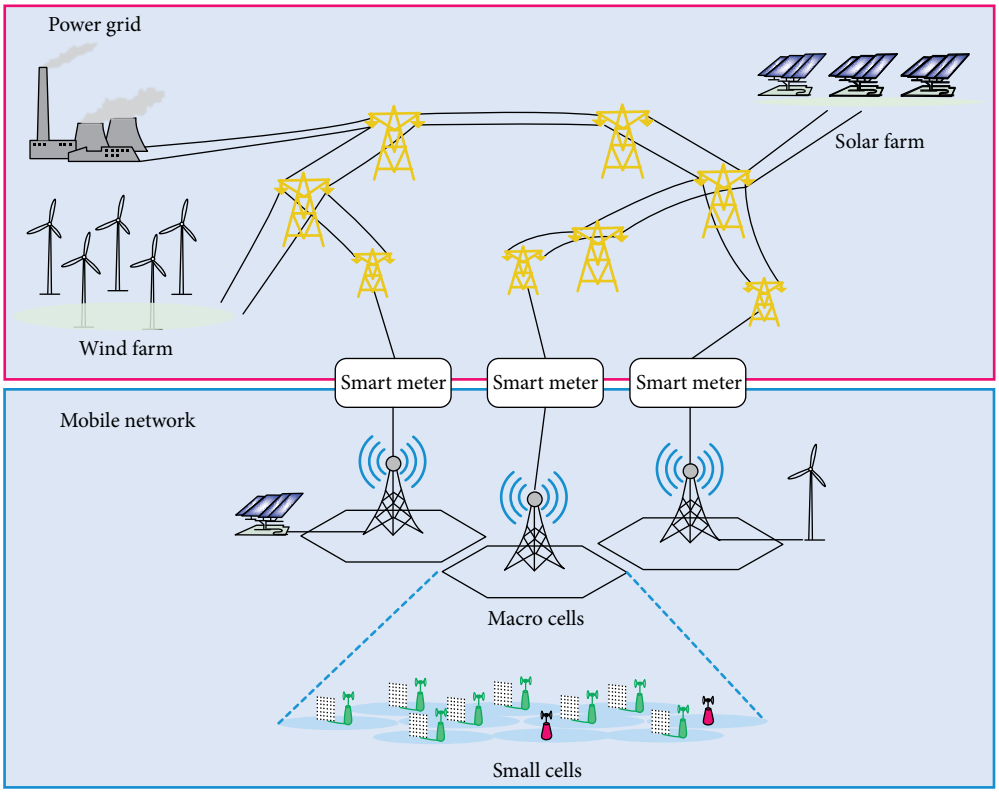

FIG. 10.4
Powering mobile networks with green power (Han and Ansari, 2014).

renewable energy farms. Meanwhile, smart grid (SG) techniques ensure the power tradeoff among the consumers via smart meters.

When BSs are equipped with RERs, there could be an imbalance in the level of RE availability between adjacent BSs, e.g., one BS has excessive stored renewable energy while others have a shortage of it. Therefore, if excessive renewable energy is exchanged with shortage, then an overall balance can be achieved. In Farooq *et al.* (2017), a framework to create this general balance between the network regions has been proposed.

Finally, the RE power can be seen as a source of revenue by the operators, e.g., by selling the excess energy to the grid—a use case particularly well fitted for developed countries with mature energy markets.

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Introducing renewable energy to power cellular network base stations makes not only environmental but also—most importantly—economic sense while at the same time opening opportunities for new business models.

Continuous advances in green energy technologies are improving the efficiency of generating electricity using renewable sources and are at the same time driving down the cost of deploying a green power system. Therefore, green energy will be a promising energy alternative for future mobile networks.

10.5.2.2 Renewable energy in data centers

Data centers are designed to support high performance computing applications, and they are a major consumer of electricity. Internet, cloud computing, and big data technologies have introduced many applications that become part of our modern lifestyle. Social media companies, e.g., Facebook, LinkedIn, Twitter, and YouTube, as well as email service providers, e.g., Gmail and Yahoo, heavily rely on data centers to store and retrieve data. In data centers, different components consume different amounts of power. According to the study by Zhang *et al.* (2016), most of the energy consumed in data centers (about 80%) goes to operating servers and cooling equipment. Therefore, RERs could help optimize the power consumption and render it economic.

Naturally, the size and the number of these data centers will continue to grow, and, currently, data centers are seen as a fundamental component in the ICT industry's next phase of growth (Andrae and Edler, 2015).

There have been endeavors and many innovative techniques proposed and implemented to manage and reduce electricity consumption as well as CO_2 emissions from data centers; these attempts have been widely reported in Jin *et al.* (2013) and Andrae and Edler (2015).

A comprehensive study by Andrae and Edler (2015) shows that data centers will use around 3%–13% of global electricity in 2030 compared to 1% in 2010. However, as the trend of using renewable energy is increasing it is likely that many data centers can be run and considered as environmentally friendly.

The electricity usages for data centers are shown in Fig. 10.5.

10.6 RE IN ICT—CURRENT STATUS

Many ICT companies are switching to renewable energies in their own electricity supply, they are doing this faster than any other sectors in the whole grid, and tech companies are often in a leading position of commitment to purchase clean energy. Twenty Internet companies have been identified by Greenpeace as companies that have made 100% -renewable energy commitments; the companies include big names such as Google, Facebook, and Apple (Clicking Clean, 2016).

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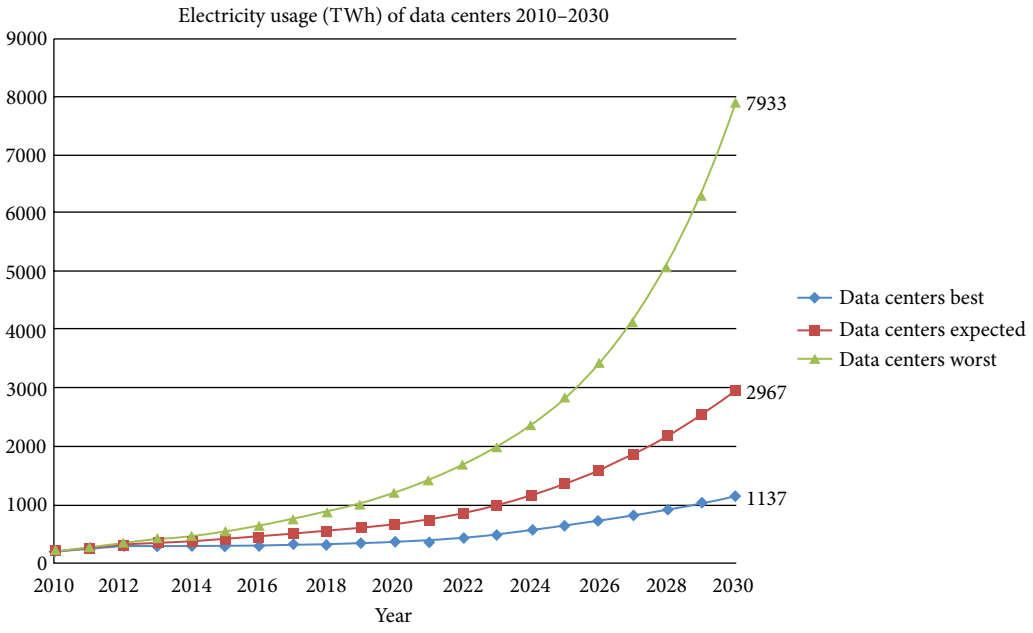

FIG. 10.5
Global electricity demand of data centers, 2010–2030 (Andrae and Edler, 2015).

In 2018, Google and Apple fulfilled their 100% power consumption by either purchasing or generating enough electricity from renewable resources ("Environmental Report," 2019). Figures and statistics from IEA show that almost half of the renewable global procurement in the last few years were accounted for by large technology companies as shown in Fig. 10.6. Among these technology companies, the top four corporate off-takers of renewable energy in 2019 were all ICT companies, with Google being in the lead position (Bloomberg NEF, 2020). Tech companies are also finding novel ways to procure clean energy. Microsoft had a plan to power 60% of its data center energy usage with renewable energy by the end of 2019 (https://www.datacenterdynamics.com/). The company further plans to reach the 70% mark by 2023. Since 2018, half of its energy usage has come from renewable sources. An ambitious plan was announced by Microsoft to be carbon negative—across its entire supply chain—by 2030, the plan commits the company that by 2050 the entire historical emissions across the life of the company would be removed (Smith, 2020).

Continuous advances in green energy technologies are improving the efficiency of generating electricity using renewable sources and are at the same time driving down the cost of deploying a green power system. The efficiency of generating electricity using renewable sources is improving. This trend is driven by the continuous advances in green energy technologies, which also helped have the cost of deploying a green power system go down.

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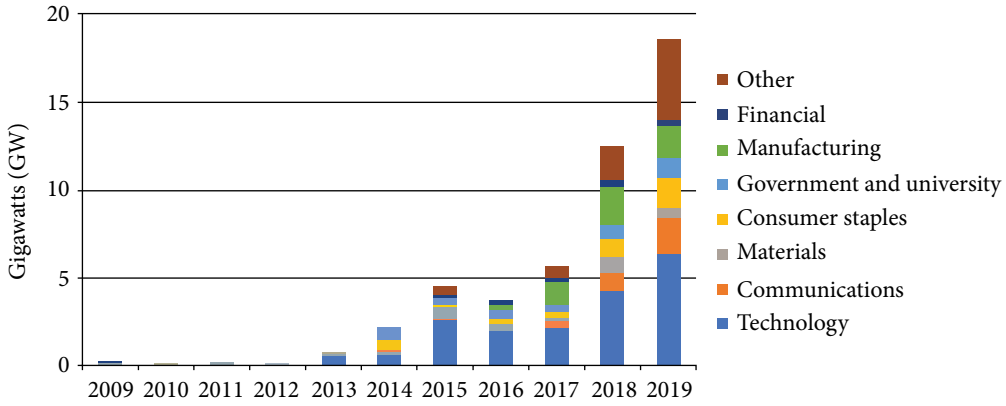

FIG. 10.6
Global power purchase agreement volumes by sector, 2009–2019 (IEA).

10.7 IoT AND ENERGY HARVESTING

The Internet of Things (IoT) refers to the use of intelligently connected devices and systems to leverage data gathered by embedded sensors and actuators in machines and other physical objects. It is predicted to include billions of devices and many experts refer to the IoT as "the next industrial revolution," one that will change the way we live.

The arrival of the IoT will see the demand for clean and sustainable energy increase; therefore, it is useful to explore alternative energy strategies, including harvesting from non-classical renewable sources from natural phenomena.

Harvesters are essentially transducers devised to extract energy from physical phenomena. Energy harvesting systems can gather energy from sources available in industrial or other environments such as mechanical vibration, temperature gradients, natural or artificial light, elevated levels of noise, and pipes with air or water fluid. Then, this energy is managed and stored to be used to feed an electronic device.

Energy harvesting techniques are becoming popular and widely used in sensor networks. Sensors, which are small digital devices, form the building blocks of IoT networks. Large numbers of heterogeneous digital devices and communication nodes are being incorporated into the Internet to manage smart cities and various service activities.

In practice, it is difficult to connect each sensor to a power source individually, and, therefore, batteries have been continuously used for convenience despite their disadvantage in terms of power cost.

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However, it is actually impossible to keep replacing the batteries connected to sensors many times on the scale of the billions of Sensor Universe. Thus, these small devices must operate autonomously over a long period, depending on the renewable energy to power them, so they use energy harvesting techniques extensively to obtain the required power for operation.

The harvesting technologies have varying degrees of harvesting capacities and efficiencies, and they can "scavenge" energy from the local environment or even from RF signals themselves, providing renewable energy to power huge numbers of IoT devices (http://www.whebgroup.com/5g-and-sustainability/).

The main aim of energy harvesting is not to produce power at a large scale but to save the harvested energy in a storage device and use it later in the daily operation of an electronic system.

One main issue with the harvesters is the low efficiency; for some type, it is as low as 10%. However, numerous studies have been going on to improve this (Pozo *et al.*, 2019).

10.8 5G SYSTEM

5G networks are characterized by small cells and cell densification, which means there will be a very large number of BSs to support small areas with a huge amount of data; therefore, reducing power consumption in this network would be very beneficial to the operators as well as the environment and keep the cost low for consumers.

The emergence of the 5G network will lead to a multi-fold increase in the number of connected devices. This will lead to a significant rise in the power consumption by the network. Thus, it is crucial to implement a sustainable network with renewable power sources, optimum utilization of power, and minimum power leakage.

Each evolution of mobile infrastructure delivers a step change, so 5G is massively more efficient than its predecessors. Energy dominates operational costs for network and data center operators, which strongly motivates good stewardship. Adherence to relevant standards like ISO50001 is exceptionally high.

10.9 ICT ROLE IN INTEGRATING RENEWABLE ENERGY SOURCES IN ENERGY SUPPLY

In Secs. 10.4–10.8, we discussed the various ways RE helps to implement and expand ICT services by providing cheap and flexible to adapt energy resources to wide geographical areas and by supplying the national grid with low-cost energy.

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However, energy systems themselves are increasingly going digital, improving efficiencies, and making devices smarter and more connected. In this section, we will look at different ways the ICT helps energy systems to become more flexible to integrate new energy sources into their operation, including RE.

10.10 ICTs FACILITATE INTEGRATION OF RE IN THE GRID

10.10.1 Smart grid

The Smart Grid (SG) defines the next-generation of the electric grid, and it combines information and communication technologies (ICTs) and control systems with the power grid.

A smart grid is a digital energy management system that controls the generation, storage, and distribution of electricity within a connected system. It incorporates a bi-directional information and energy grid with digital connections to all of its components in order to be in a position to balance electrical supply and demand over the range of its control.

Smart Grids (SGs) are expected to be a key enabler in the integration of Renewable Energy (RE) sources in the electrical networks.

In contrast to the conventional power grid, the smart grid makes it possible for distributed and intermittent energy sources (such as renewables) to be easily attached to the backbone grid and fuse with the conventional fossil fuel sources. Thus, a widely distributed and automated energy delivery network is created (Cao and Yang, 2013). It makes use of local and distributed power-storage capability to smooth out the intermittent performance of renewable energy sources.

Electric energy suppliers are considered as the main suppliers of mobile network operators with energy for their network operation. However, the dependency of MNOs with regard to energy suppliers may decrease as MNOs deploy RE sources on their BS sites. However, the integration of BS sites in the smart grid is predicted to increase the interaction between MNOs and energy suppliers. For example, this allows for the excess local generated RE to be fed back to the smart grid, making the MNO an energy supplier within the smart grid. Storage capacities in BSs could also be used for storing the excess energy generated in the smart grid and vice versa. The introduction of RE-powered BSs with local energy storage systems motivates further development of common policies between MNOs and the smart grid to increase their mutual benefit, possibly offloading and selling excess RE generation back to the grid.

To improve the quality of service of the electrical energy distribution and to exploit distributed energy resources (including RE distributed generation), real-time monitoring of the power grid should be extended to include secondary substations, medium voltage, and low voltage grids, up to end-users, gathering and processing all these data where they are really needed.

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10.10.2 Conventional electric supply

However, one of the major challenges faced by electricity companies is the lack of interoperability of the different communication systems deployed in different SG segments. In order to resolve this interoperability challenge, there were proposals such as the interoperability project the U.S. National Institute of Standards and Technology (NIST) has worked on (IEEE P2030), and this project dresses interoperability issues related with the integration of power systems, energy resources, and information technology (IEEE P2030, 2010).

It has been a well-known fact that communication systems play an important and a vital role in the integration of renewable energy resources into the smart grid. It would not be possible to ensure two-way communication, which is an integral part of the future SG without these communications. ICT architecture is designed to efficiently fulfill both communication and application requirements foreseen for the smart grid.

10.11 ROLE OF ICT IN SUPPORTING RE IN REDUCING POWER CONSUMPTION (INDIRECT SUPPORT)

ICT is at the heart of many solutions that reduce energy demand and CO_2 emissions. The expansion in the use of ICT and telecom devices resulted in a new style of work and business activities, such as telework and teleconferences, which led to reduction in business travel. This may result in ICT to achieving net reductions in global energy use and environmental impact. As digital services continue to replace traditional non-ICT activities, the expectation is that the ICT may already yield net reduction in global energy consumption and carbon emission.

The use of ICT in buildings would enable smart use of energy and help create smart cities and smart environments; this could be applied to transportation, manufacturing, and other areas. Widespread digitalization of homes and commercial buildings could reduce annual electricity demand by nearly 25% (Cunliff, 2020).

Dematerialization, which is a concept that refers to replacing physical goods and in-person activities with equivalent digital services, is one of the methods through which ICT can reduce energy and environmental impact.

Emails and websites have replaced many physical activities and shortened time of services. Digital platforms enabled telecare, telework online teaching, and e-commerce, which resulted in less commuting and fewer vehicles on roads and reducing fuel consumption. ITIF's report Digital Quality of Life provides a thorough review of how ICT is saving energy and reducing environmental costs through dematerialization (Atkinson and Castro, 2008).

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10.12 POLICIES

The electric power consumption in ICT and Telecommunication sector is quite small compared to other industrial sectors; nevertheless, issues related to policy and regulation are of utmost importance as an increase in ICT and telecommunication hardware deployment adds considerable addition to power consumption.

The European Commission introduced certain regulations for ICT with the objective of reducing CO_2 emissions. The Commission introduced the instrument of the so-called CoC (Samdanis *et al.*, 2015) on a voluntary basis. The CoC contains the policy of maximizing the energy efficiency of ICT equipment. Service providers, network operators, equipment, and component manufacturers may voluntarily commit to the CoC by signing as individual companies. However, the document has no mention of the renewable energy usage in providing a certain percentage of power-to-power ICT equipment.

As the market for mobile communication and ICT is growing globally, governments around the world should aim to implement effective energy policies and adopt regulations that encourage businesses to invest in renewable energy and market it to Telecom and ICT operator, especially in regions with no electricity service coverage

Governments and regional authorities' energy policies should also identify energy resource that is available, in particular, places and sites considering technical and economic feasibility. Additionally, hybrid energy renewable sources (solar, wind, batteries) should be considered for use in radio BS in developing countries according to natural energy resources available in those countries.

The policies should include other government departments, such as health, education, and other public sector institutions, to ensure consistency and coherence that will benefit the majority of people. The policies should be smart enough to decide whether tax exceptions or similar strategies should be considered and be taken into account in the ecosystem to improve and reduce the emission of any greenhouse gases.

Finally, having RE-powered BSs with local energy storage systems encourages the development of common policies between cellular network operators and the smart grid to increase their mutual benefit, possibly offloading and selling excess RE generation back to the grid.

10.13 CONCLUSIONS

Employing renewable energy is not only environmentally friendly but also has other benefits, with one of the notable points being the shift from energy efficiency to energy sustainability. This work presents a review of the global electricity usage that can be ascribed to Information Communication

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Technology (ICT) and the way this consumption could develop until 2030. Some studies in the review show, for the worst-case scenario, that ICT could use as much as 51% of global electricity in 2030. However, until 2030, the globally generated renewable electricity is likely to exceed the electricity demand of all networks and data centers. Tech companies are getting clean and green energy faster than other businesses, and the ICT sector is the leading industry in setting targets for what is known as a sector-wide science-based decarbonization. Energy systems are becoming smarter and more connected through the integration of ICT, which utilizes different techniques such as data analytics and advanced controls to improve energy efficiency and reduce the environmental impact on industries, businesses, homes, and offices.

As the demand for energy to supply ICT increases, governments and stakeholders all over the world have the responsibility to put in place policies and regulatory frameworks that will encourage and attract investment into renewable energy technology to support the ICT sector to achieve the environmental preservation target and to stabilize prices in the sector.

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CHAPTER

11 RENEWABLE ENERGY MANAGEMENT AND ECONOMICS

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11.1 INTRODUCTION

A total work of energy management through the preparation of different sources of renewable energies is researched via good researchers such as Bussar *et al.* (2016) who investigated the adopting flexibility of different renewable energies to supply a standard value of security within matching the supply and demand in any time. Mengova (2019) has determined the production of energy of varied renewable energies to analyze the principal barriers facing the move toward a quite cost-effective and environmentally friendly state. Kebir *et al.* (2019) have investigated an accurate and fast real-time optimization (RTO) technique to control the production of varied renewable energy sources (RESs), and on the other side, a methodology design of multiple renewable power sources-based hybrid energy systems is given (Feroldi and Zumoffen, 2014) for developing a planning model of power generation for considering a penetration of wide renewable energy sources (Luz *et al.*, 2018). A novel algorithm of the analysis to determine the amount of renewable energies at a wide transmission network is achieved (Obara *et al.*, 2018), and a model of a microgrid for integrating the power plants of renewable energies to employ PVs to optimize renewable energies' utilization of area of an on-grid area is displayed (Nazir *et al.*, 2014), in addition to implementing a system of multi-agent for controlling, coordinating, generating, and consuming renewable energies (Xiong *et al.*, 2020).

It is important to research and study the interrelationship between ecology, environment, and organisms for a specific goal. The composition of the abiotic and biome environment is called an ecosystem (Blamey *et al.*, 2015). Actually, the ecosystem has different similarities; it is a summation of biological and environmental systems. The biome is a basic state of the environment that could be affected by the

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environment. The environmental reformer and environmental adaptor could form a biological system (Aokiyoshida *et al.*, 2016). The ecosystem is composed of non-biological and biological components. The subjects could be symmetrized for natural biological elements and the environment for non-biological elements. The ecosystem has a likeness among the processes of dynamic circulation, cycle of energy, and transformation of materials. Exchange, subject, and ecological environment constitute a unity—through the exchange of knowledge—to be an ecosystem of knowledge. As a critical approach to ecology, the ecosystem focuses on the ecosystem, internal and external interactions to explore the ecosystem, micro-, macro-, and mesolevels of development (Tao *et al.*, 2018).

It seems that electric storage and energy storage are more promising and challenging than the storage of thermal energy because of the higher quality of electrical energy in comparison to thermal energy. The systems of electric storage include compressed air storage, electrochemical energy storage, pumped storage, and supercapacitor storage. Due to the development in techno-economic competitiveness and technology, the storage of electrochemical energy has been utilized like lithium-ion batteries and lead-acid. The depreciation of batteries in the energy of interactive renewables–buildings–vehicles is a critical factor affecting the penetration of renewable energy, building demand coverage, the capability of electrical shifting of an off-peak grid, and the power grid ramp rate. In literature, the mentioned knowledge and information on the depreciation of batteries are rare. The formulation of the control strategy of advanced energy for decelerating the depreciation of batteries is recommended for the enhancement of system performance (Esfetanaj and Nojavan, 2018).

The cost-effectiveness of incorporating the forecasting of a short-term wind speed, load demand, and solar irradiance in the operating system is attractive. Hodge *et al.* (2018) have researched an outlook of expected power for providing the necessity for an intelligent schedule of various components including loads. Wu *et al.* (2015) have discussed the benefit of demand-side management (DSM) in terms of planning and flexibility of the energy market. Therefore, the optimal schedule of the flexible demand resources' (FDRs) via a system of microgrids can grant enough flexibility. The mentioned benefit can reflect the economy of size and cost of electricity storage for customers. Anyway, the implementation of DSM, especially for FDRs, can be achieved with the generation of renewable energies. For future generation of electricity, the client could benefit for energy demand from flexible prices for reducing the consumption of energy.

The competition analysis of the markets of electricity including renewable energies has guided to the following result; it is expected that the average price for renewable energies will fall below the traditional prices—whenever supplying renewable energies exceeds the required demand and market prices of short-run electricity will equalize the renewable energies' marginal cost. For supplying long-term investment, the mechanism is necessary to reply on other than a short-run for determining the payments for renewable energies without taking into account the location and time. It is observed very well that the auctions for investment in renewable energies are quickly extended worldwide (IRENA, 2019). The main features of auctions including auctioned-off products such as capacity, energy,

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technologies set, or price exposure of winning projects are permitted for competing and determining the success of auctions. Also, because the renewable energy culture is not disseminated enough and not available completely, their distributions are associated traditionally with the necessity of avoiding energy disruptions. Anyway, many effective solutions to adopt with renewable energies are coming from either the supplier side or the demand side, such as utilizing the prices of dynamics for inducing the energy consumption toward hours of high production of renewable energies. Both ideas can mitigate the extra need for maintaining huge capacity. Particularly, the mechanism of demand response induces the shifting of load from high-price, including low renewable energies/high demand, to low-price, including high renewable energies/low demand. The technologies of storage could assist to address renewable energies via permitting the storage within periods of renewable energy abundance and releasing within the times when they are rare. Anyway, some of the issues deserves more interest and research. Although there is a strong theoretical argument related to the pricing of dynamics (Zhao *et al.*, 2021), the experimental works that have illustrated the demand for active response are not necessary in the absence of technology (Harding and Sexton, 2017; and Fabra *et al.*, 2021). For energy storage, the problem is not in its high cost but in the creation of distortion for efficient investment and operation (Chen *et al.*, 2018). Both theoretical and experimental works are very integral to renewable energy's dissemination, as renewable energies will enlarge price and cost volatility to enhance the private and social benefits of demand storage and responses.

Among the many energies' demand and transformation sectors, the reduction in CO_2 emissions from the power generation sector is regarded as particularly important for the deep decarbonization of energy systems. To achieve Japan's official decarbonization target [Ministry of the Environment (MOE), 2016], for example, which is the reduction in greenhouse gas (GHG) emissions by 80% from the current level by 2050, it would be essential to almost entirely decarbonize the power sector, as shown by the results of multiple simulation models, including AIM/Enduse (Masui *et al.*, 2016), AIM/Backcasting (Ashina *et al.*, 2012), and DNE21+ (Turconi *et al.*, 2013; Akimoto and Sano, 2017; and Fuss *et al.*, 2018). The reason for this lies simply in the fact that energy carriers other than electricity are considerably more difficult to decarbonize (Sugiyama *et al.*, 2019).

To assess the economics of heat pumps, a "load cost" metric is introduced. For identifying the wind power market value, the heat pumps' load cost is a marginal cost to the electrical system for serving one MWh consumption of pumps of heat. It is expected that the total cost of electricity from using wind energy is to reduce the cost of pumps of heat. Due to this, the cost of margin to supply the pumps of heat will be reduced for the availability of wind energy. To amplify the mentioned benefits, heat pumps' flexible operations are employed. Otherside, the necessity for costed capacity mentions high margin costs to supply the pump of heat. Henceforth, the total dream of the cost of pumps of heat remains really ambiguous. The economic ambiguities of wind energy and the pumps of heat address the following: (1) How to develop the cost of the pump of heat as a function of expansion of the pump of heat? (2) What are the impacts of pumps of heat on wind energy market value? (3) What are the impacts of technology of thermal storage and pump of heat on the general economy?

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11.2 SOURCES OF RENEWABLE ENERGY

It is designed and investigated to study the investment impact of suppliers in varied sources of renewable energies for the maximum capacity of storage in two regions including six south and north cities with different consumption and climate as an example. Normally, each city has different consumption because of the many demands of consumers. Table 11.1 presents the results of two distributors and three suppliers for three northern cities.

The two sources belonging to supplier 1 of energy storage are presented in Table 11.1. The maximum capacity of solar and wind energy is 790 and 273.25 MW, respectively. For Nineveh, the optimum storage is 353.25 (45% * 785), which is higher than Kirkuk and Salahuddin cities because of the high number of consumers. Additionally, the increase in the MW capacity for energy storage is inevitable

Table 11.1
Simulation output of northern cities (Kirkuk, Salahuddin, and Nineveh) (Mohammed and Al-Bazi, 2021).

Details	Renewables	Production	Amount of energy storage Northern region (%)			Max-storage capacity (MW)
Supplier S	Sources type r	Min-Max (MW)	Nineveh C_{11}	Salahuddin C_{12}	Kirkuk C_{13}	SC_{max}
1	Solar	0–790	45	45	19	785
	Wind	9–273.25				
2	Solar	0–237.99	32	32	51	535
	Hydro	193.5–260.57				
3	Wind	16.2–427	33	33	19	780
	Hydro	261.3–351.7				

Table 11.2
Simulation output of southern cities (Thiqar, Misan, and Basrah) (Mohammed and Al-Bazi, 2021).

Details	Renewables	Production	Amount of energy storage Southern region (%)			Max-storage capacity (MW)
Supplier S	Sources type r	Min-Max (MW)	Basrah C_{41}	Misan C_{42}	Thiqar C_{43}	SC_{max}
1	Solar	0–928.7	47	23	30	825
	Wind	18.1–1189.8				
2	Solar	0–237	28	48	24	650
	Hydro	16.2–1427.76				
3	Wind	8–500	47	36	17	750
	Hydro	21.34–104.75				

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when wind energy is taken into consideration. For the southern cities, the simulation result of two distributors and three suppliers is displayed in Table 11.2.

11.3 OPTIONS OF DIFFERENT CONSUMERS

The performance of the consumer effect for different distributors of the whole system is investigated in the two regions of cities (south and north). Figure 11.1 illustrates the weekday results of summer for three northern cities of Salahuddin, Nineveh, and Kirkuk. It is known that all of these mentioned cities have varied requirements, nature, and consumption. For Salahuddin city, it is agriculture; for Kirkuk city, it is industry; and Ninevah, it is the second city in Iraq that has a high population and big consumption of energy via thousands of households.

Here, Table 11.2 presents the energy levels created via a source of wind energy in the southern cities of Thiqar, Misan, and Basrah, which are higher because of the suitability of the climate for utilizing renewable energies. Basrah represents the highest storage of energy because it is the biggest city in the south of Iraq with a big area, high population, and huge consumption of energy.

Figure 11.1 shows the difference in the behavior of consumers of the three cities, Kirkuk, Nineveh, and Salahuddin, explained through the different curves of demand. But the curve shape of the demand of the distributor DI1 has tariff and time is smoother than distributor DI2. The residential consumption-type city has a high ability to lessen the purchase of energy in time of peak load from DI1. Figure 11.2 compares the energy distribution and consumption in the three cities: Basrah, Missan, and Thiqar. The weather is humid and warm in summer.

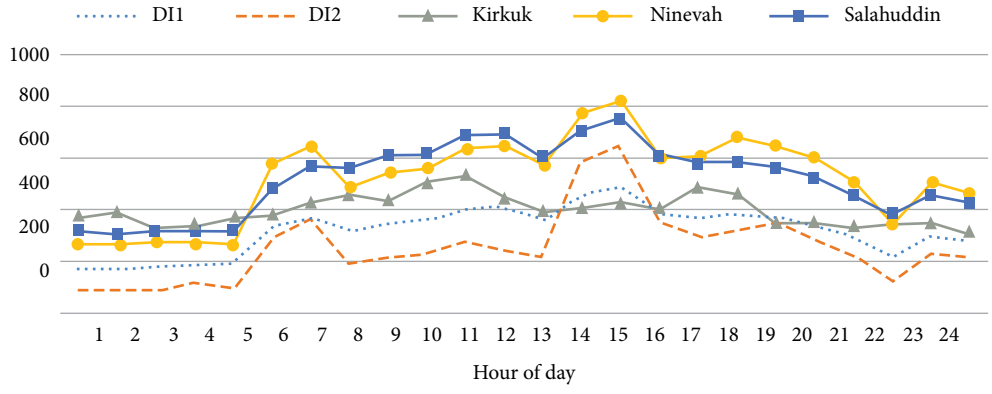

FIG. 11.1
Comparison between energy consumption and distribution in northern regions—Nineveh, Salahuddin, and Kirkuk cities (Mohammed and Al-Bazi, 2021).

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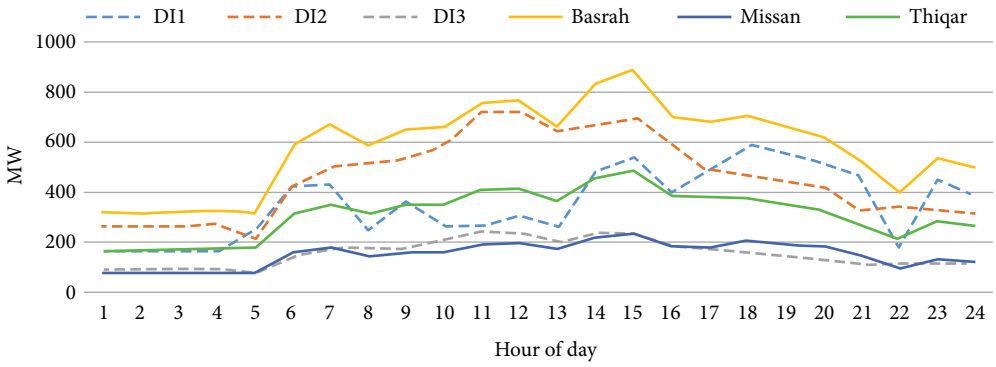

FIG. 11.2
Comparison between energy consumption and distribution in the southern regions—Basrah, Misan, and Thiqar cities (Mohammed and Al-Bazi, 2021).

The cities in the south of Thiqar, Missan, and Basrah have different consumption requirements. Hence, the city of Basrah represents a higher consumption of energy due to its big area and high population, different from others in terms of area and energy consumption. The other cities are located geographically in the middle of Iraq, Diala and Anbar; Fig. 11.3 compares three suppliers and two distributors for the mentioned two cities.

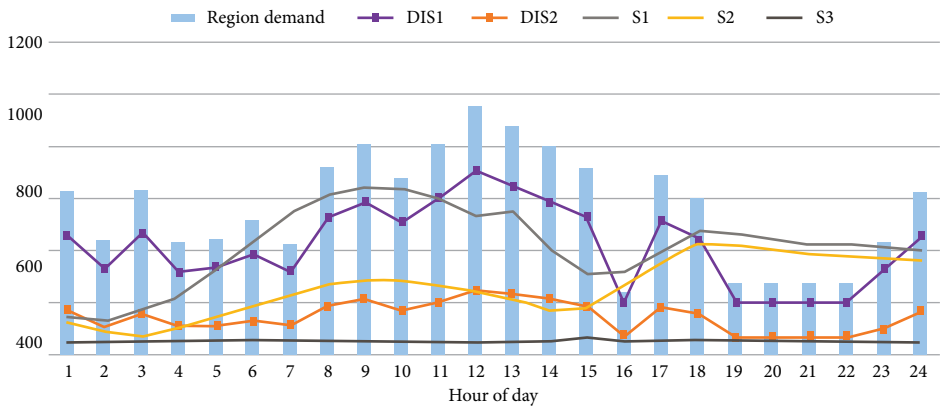

FIG. 11.3
Comparison between energy production and consumption in the middle regions—Anbar and Diala cities (Mohammed and Al-Bazi, 2021).

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Figure 11.3 shows the curve of load for energy represented by distributor 1; DIS1 is smoother and with less fluctuations than the production of energy of supplier 1 S1, which has big fluctuations than that of supplier 3 S3. The curve of the load of distributor 2 DIS2 is smoother than suppliers 2 S2 and 3 S3, respectively. The mentioned results illustrate the energy impact volume provided by distributors to consumers.

11.4 IMPACT OF ECOLOGICAL ENVIRONMENT ON RESOURCE-BASED RURAL AREAS

The system of different rural collaborations can be explained as a system of overall composites that constitute three different subsystems of ecological environment, human society, and economic benefit. Regarding the systems of ecological environmental characteristics, it has a specific range of regulation functions and self-repair, but the civilization construction of artificial ecology can enhance the ecological environment of human settlement in the countryside. Hence, the ecosystem is a specific system of positive feedback. Anyway, both human society and economic benefits are adjusted systems for a specific goal. The system's role is a reflection of stability and regulation effects. The environment of ecology has a function of self-repairing, leaving the other two ecological environment systems to exist independently to continue their operation. This relation mentions the system of ecological environment and attributes to its own system of positive feedback. Hence, whether it is human society or economic benefits, it will fail and become inoperable when you are leaving the two systems. It confirms the characteristic system of human society's own negative feedback and economic benefits. It is easy to observe the human society and economic benefits constitute a system of positive feedback; ecological environment and human society constitute a balanced system; and an economic system and ecological environment also constitute a balanced system. This illustrates that the ecological environment has a crucial role in the economic and ecological developments of source-based villages. As illustrated in Fig. 11.4, the GDP of China increases yearly.

Based on the consumption of energy as illustrated in Fig. 11.4 and related to the structural consumption of energy in the China Energy Statistical Yearbook, the consumption of energy for the period 1953–2010 is divided as follows: 1953–1977, 1978–1989, 1990–2001, and 2002–2018. The probability matrix of Markov transition is gained via utilizing the constraint method of least squares in the mentioned stages, and the causes and rules of the consumption structure of China's energy change are investigated as a combined background of economic policy, where the probability matrix of Markov transition of the four mentioned stages is verified by the correlation of rank, and their changing characteristics and internal relations are studied.

The increase in central Europe energy partners (CEEP) mentions a lack of system flexibility. To regulate the planned generation of offshore wind energy, CEEP is set to 0.5 TWH/yr. As illustrated in Fig. 11.5, the worst system flexibility is the biodiesel option, followed by the hydrogenation of biomass. This

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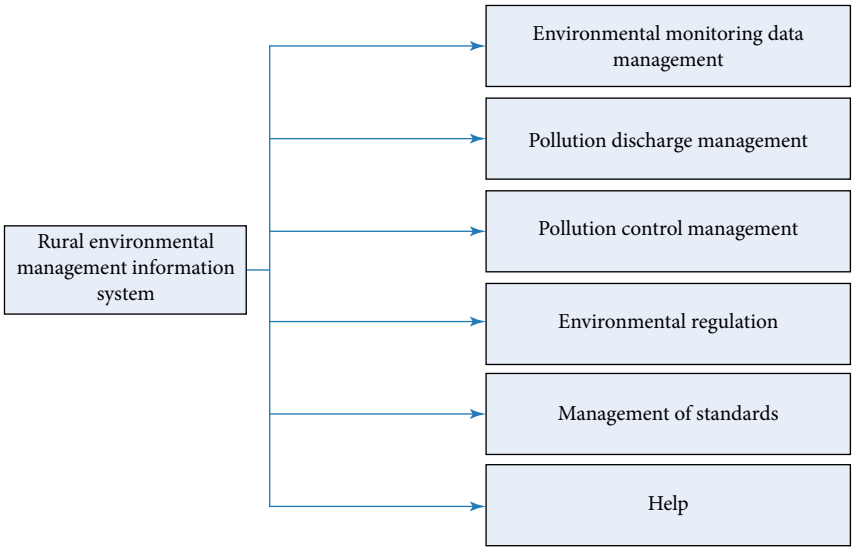

FIG. 11.4
Function module design (Zeng *et al.*, 2021).

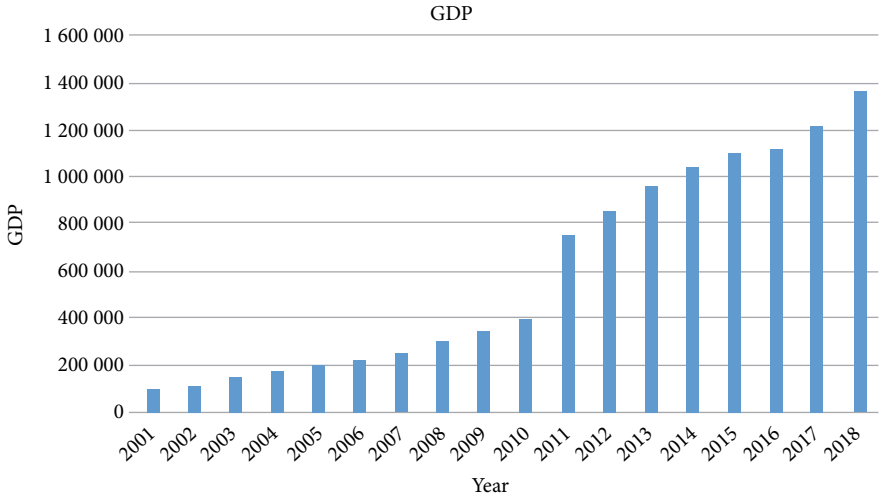

FIG. 11.5
China's GDP trend from 2001 to 2018 (Zeng *et al.*, 2021).

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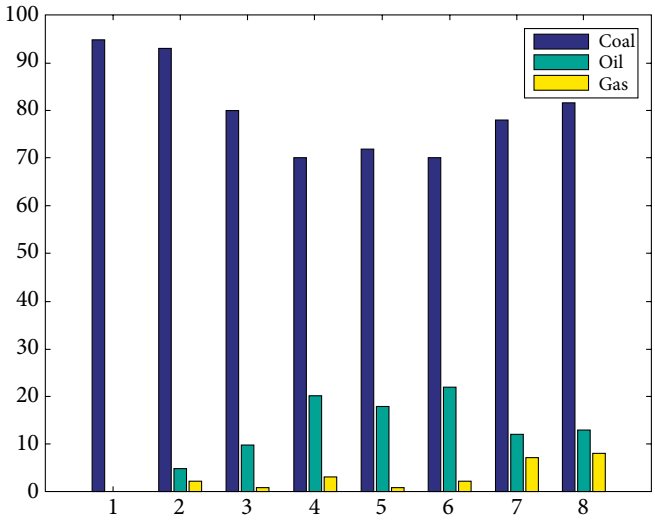

FIG. 11.6
1953–2018 China's energy consumption composition (Zeng *et al.*, 2021).

displays the more integral of wind energy guides to the extra increase in CEEP. Hence, CEEP reduces as the capacity of storage increases (Fig. 11.6).

Figure 11.7 illustrates an energy supply of annual primary without renewable energies like the consumption of biomass fuel, although the transmission line input and power plant capacity and the demand of specific powers for electrolyzer installation did not result in a higher supply of primary energy in the schemes of hydrogenation of carbon dioxide and co-electrolysis. After the system attains a specific capacity of wind energy if the biomass and biodiesel are hydrogenated, the system flexibility is less than the integrated cell due to the consumption of the same biomass fuel residues, and CEEP resumes to rise.

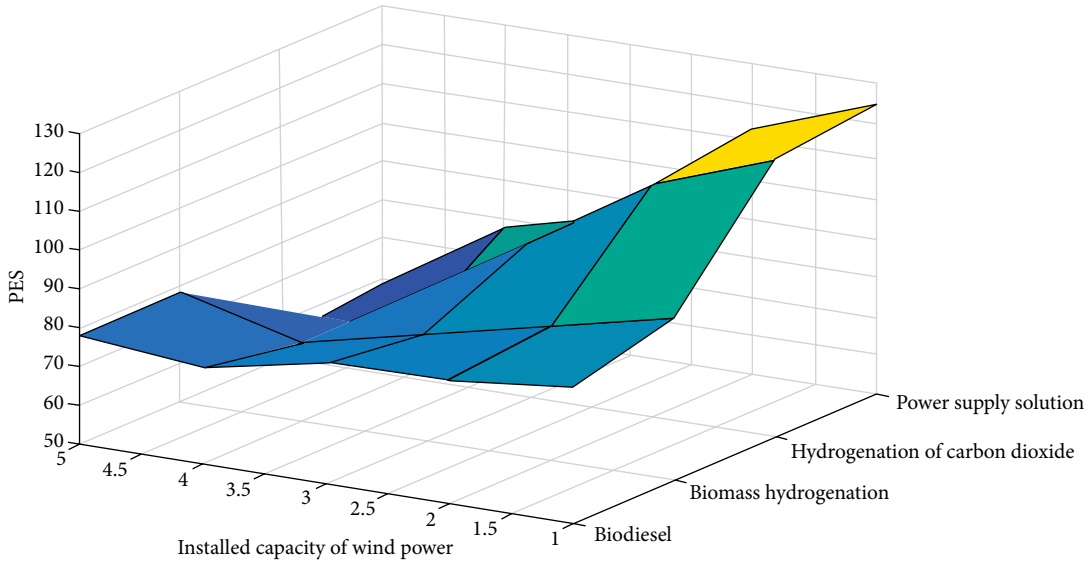

FIG. 11.7
China's biomass fuel consumption (Zeng *et al.*, 2021).

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11.5 ACCURACY ASSESSMENT AND COMPARISON

To study the cost parameter compared with research and academic results, it is very necessary due to its sensitivity to the market prices of electricity. Instantaneously, as the price of electricity increases observably from 0.3 to 0.9 HK$/kWh, the cost of import too increases from 78.5 to 112 HK$/m^2 (Schorn *et al.*, 2021), while a very clear increase is observed from 49 to 245 HK$/m^2 in the current study.

This increase is attributed to the huge demand for different buildings, which is bigger than the demands for single offices (Schorn *et al.*, 2021). Moreover, as the demand for renewable energy increases from 0.2 to 0.8 MW, there is a noticeable decrease in money for 100–23 HK$/m^2. That is attributed to the huge loss of charging of batteries for the accumulated system of vehicles-buildings than the system of single vehicles-buildings (Schorn *et al.*, 2021). Moreover, following the published data (Turconi *et al.*, 2013; Ogunjuyigbe *et al.*, 2016; Delgado *et al.*, 2017; Litjens *et al.*, 2018; Roberts *et al.*, 2019; Sugiyama *et al.*, 2019; Cárdenas *et al.*, 2021; Schorn *et al.*, 2021; Tanoto *et al.*, 2021), the reduction in the cost of operation will increase the penetration of renewable energies, while a huge increase in the loss of charging of batteries will emerge. From an energy flexibility viewpoint, Zhou and Cao (2020) have integrated and adopted solutions for enhancing the energy flexibility of buildings, including conversion strategies of diversified energy, electric storages, and hybrid thermal. They have mentioned that the integrated systems of electrical and thermal storages and the amelioration of the capacity of storage will enhance the fraction of on-site flexibility. The obtained results are found to have similar trends and another magnitude (Schorn *et al.*, 2021). That other magnitude is attributed mainly to the extension of the boundary system of energy and implemented a control strategy for the protection of batteries. Additionally, it is found (Akter *et al.*, 2017) that an increased storage of the battery will lessen the reliance on grids. The performance of different criteria (a matching of energy is between demand and renewable energies, cost of operation, and others) highly relies on the degradation of batteries and the strategical management of energy of the battery. The neglection of degradation of battery has overestimated the saving cost of buildings to vehicles in spite of increasing penetration of renewable energies as highlighted by Salpakari *et al.* (2017). The flexibility of energy is supplied by the system of energy storage of battery as studied by Aelenei *et al.* (2019). The battery power of 13.5 kWh results in good monetary values estimated to be 1416.1 EUR with ratios of self-sufficiency and self-consumption of 62.4% and 56.3%, respectively. To optimize the rate of discharging and charging of batteries to be cost-effective, Phan *et al.* (2018) have presented their related research. To adopt the algorithm of genetics, the daily cost can reduce to 31%. Liu *et al.* (2018) researched to conduct the optimization of multi-objectives of modes of charging (variations of temperature, speed of charge, and efficacy of conversion of energy) for managing intelligent batteries related to the rise of temperature, loss of energy, and time of charging. The suggested solutions of Pareto fronts can supply guidance on techniques for operating the systems. From the adopted technological viewpoint, the research has indicated an efficient strategy of improved eco-technology performance for integrated systems of

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energy in buildings including thermal photovoltaic systems (Litjens *et al.*, 2018), sharing of energy technology in districts and buildings (Tanoto *et al.*, 2021), the interaction of buildings to vehicles, and strategical control of responsive grids (Pelzer *et al.*, 2014). Systematic and comprehensive reviews are achieved by Khatib *et al.* (2016) for optimum systems of batteries and PVs. There are specific methods such as artificial intelligence, numerical methods, and software tools. In comparison to others, artificial intelligence (AI) is efficient because of the big efficiency of computation and huge space of search that supports the aimed research here.

11.6 FORECASTING OF SOLAR AND WIND ENERGIES

The humidity, solar irradiance, wind speed, temperature, and wind and pressure directions represent the parameters for the solar and wind models of power forecasting (Wan *et al.*, 2015). To explain below, the approach of regression forecasting represented by Random Forest (RF) is adopted currently. It is a learning algorithm for bagging an ensemble-based machine for combining many separated models of regression trees and classification. It has the advantage of overcoming shortcomings for the tree of classical decision, which fits to all high variance and training data via a procedure of randomization (Huertas and Centeno, 2019). The elaborations of implementation and training procedures of the algorithm RF are provided in Barbosa de Alencar *et al.* (2017). The results of the prediction of models of forecasting are estimated utilizing root means square error, mean absolute error (MAE), and r2 metrics (Huang and Kuo, 2018).

11.7 INCENTIVES OF INVESTMENT IN RENEWABLE ENERGIES

There are two grounds, namely, learning-by-doing externalities and a positive environment that determine the actual support for renewable energies (Newbery, 2018) joined with the costs of the higher average in relation to traditional technology. Anyway, the breakthroughs majority of technologies have imposed are the total costs of renewable energies to have the same or lower costs of traditional technology (IRENA, 2020). The mentioned cost does not imply the investment required to take place, while the disadvantage is highlighted for the precedent section that is the core of the Classical Theory of Regulation: whenever the required costs are marginal or less, the efficient price is not allowed to break. For the future market of electricity, the prices will describe the volatility of prices, including high and low rates, renewable energies tend to aim for lower rates of prices due to the effect of price-depressing already discussed. The uncertainty prices of the future controlled by renewable energies exacerbate the mentioned issue through adding risks to the financial costs for the investment cost of high capital. An urged question is arisen, how to fabricate the instruments of policy for achieving investment in renewable energies for the best of societies.

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It is attractive that the auctions have attracted properties. The competition between investors before achieving the whole structure of investment has the capability to let the prices drive down in competition with other markets and projects; therefore, it is allowed to let all or at least the consumers to be benefited from the lower cost of renewable energies. Moreover, there is a sure possibility to reduce the total costs and charges via utilizing long-term contracts before achieving the projects and investments, in addition to letting the access for crediting easier and promoting maximum benefits via a stronger competition and reduced prices. Anyway, this is not enough for auctions to be used. As the demonstrated European experience different auctions, the auction should design in paramount: it seems small differences have big consequences on the performance of auctions (Klemperer, 2002). Although there is a variation in cross-country for auctions designed for renewable energies, there is a possibility for providing specific empirical evidences related to design choices' effects on the performance of auctions. The updated literatures have highlighted some cons and pros of different options. In the following sections, the nature of trade-offs within two keys, the approach of technology and the price exposure degrees, will be discussed.

As a small part of the design of auctions, the controller decides on exposing the investors of renewable energies to the price's volatility of the electricity short-run including estimated costs. At the mentioned extreme, the controller could decide between the exposure to full price and the insurance of full price. For providing insurance of full price, the controller could fix the prices of auctions per MWh manufactured along plant lifetime. Contracts-for-Differences (CfDs) or Feed-in Tariffs (FiTs) could serve the mentioned purpose. For CfDs, the investors could sell their products or outputs at the price of markets and receive the difference between the price of the reference market and the price's strike, which is setting *ex ante* or possible through the auctions, while, for FiTs, the investors of renewable energies are receiving limited prices for their output.

There is an important issue related to all renewable energy technologies that could be allowed for competing via similar auctions (neutrality-technology) or the auctions could be of specific technology. This case is related not toprocure renewable energies technologies such as solar and wind energies, but to procure the investment of lower carbon such as storage technology of an electrical battery in front of electrolyzers of hydrogen or to procure supply security such as generators of back-up and demand-based response. The same issues have arisen in deciding the auctions' scope of geography, which means whether the auctions are localized or not or to decide whether all the sizes of project firms and sizes should be permitted to include and participate in all auctions. So, for the mentioned extremes, there are varied schemes via specific locations, technologies, project firms, and sizes to obtain an impediment for playing field level as the banding of technology.

11.8 ADOPTING WITH RENEWABLE ENERGIES

The weather condition represents a challenge for the availability of renewable energy. Related to all network nodes, for avoiding the collapse of the system, the electricity supply should be equal at different times. It is a logic justification of why renewable energy resources make real challenges for a smooth

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management of electricity markets. Is benefited to supply security for being guaranteed when wind and solar energies are rare? It is thinking traditionally for building enough spare of capacity. Anyway, it not only costs for backing up the capacity, but also provides thermal plants that jeopardize their objectives to achieve the markets of power of zero-carbon. Moreover, it is unclear that the investors could have the ability of incentives for building rare capacities unless public support submits them (Fabra, 2018). It is very lucky that the innovation of prices and technology pave the way correctly for alternate choices: the storage and response of demand. The necessity to counteract the volatility of renewable energies is growing and consuming of the aims and goals to respond to the storage and demand for providing like buffering to become distinguished and very important.

If the windless and sunless factors really determine the storage requirement, as speculated above, it should be able to estimate this quantitatively by calculating the residual loads during the periods. The point is to calculate the storage requirements uniquely, without any detailed model simulations, from exogenous data, such as hourly electric loads and variable renewable energy (VRE) output profiles. The cumulative residual load (CRL) method uses only the total data from the nine regions and can simulate the changes in power demand and supply situation with high VRE penetrations under different meteorological conditions. When the VRE capacities are fixed, the residual load during windless and sunless periods must be met by either power discharge or firm capacity. It should be noted that the reduction in the storage requirement by the addition of the firm capacity of 1 GW is not constant but differs depending on meteorological conditions.

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11.9 THE SEPARATE ADOPTION OF WIND POWER AND INFLEXIBLE HEAT PUMPS

In view of technological variability, the markets cause a decrease in the power of wind, and the cost of loads causes an increase in the pumps of heat in terms of the high speed of wind: a big volume of the power of wind depresses the prices of electricity followed by average values of markets of the power of wind. It introduces high values of energy of the wind to reduce its pronunciation firmly. Similarly, when the consumption of electricity for the inflexible pumps of heat increases, the total demand for electricity including prices also increases; therefore, this leads to an increase in the cost of load of heat pumps. This is exacerbated by the mentioned effect through an increased adoption of pumps of heat. While the decline in the values of margins is actual to the supply of power and undesired operations of the wind farms, the increased costs in margins are inherent in the consumption of electricity for inflexible pumps of heat and unsuitable for the owners of pumps of heat.

For a much better understanding of the rising-up of load costs of pumps of heat, Fig. 11.8 illustrates an overview of variations of the installed capacities of varied technologies for the generation of electricity. It is noticed that whole installed capacities grow in a huge form in the pumps of heat that induce an increase in the consumption of electricity by presenting 15% sharing of pumps of heat,

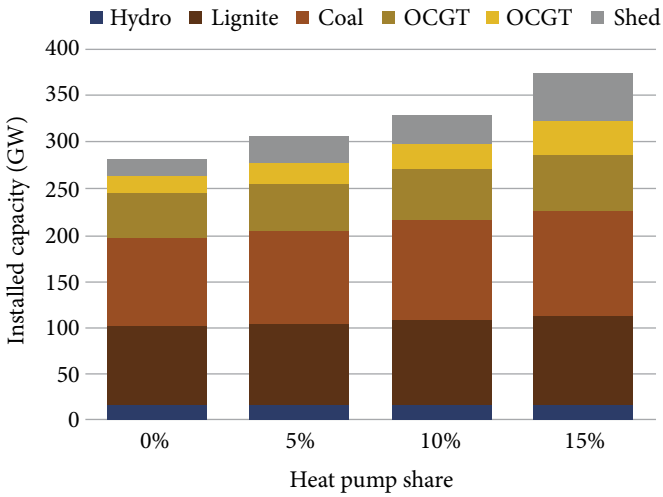

FIG. 11.8
Capacities of installed electricity generation in a model suitable for increased shares of pumps of heat. CCGT, combined cycle gas turbines; OCGT, open cycle gas turbines; Shed, load shedding (Ruhnau *et al.*, 2020).

so the capacities are enlarged by 30%. This includes an increased portion of the whole load to be shed at an extremely big price. Additionally, the expansion of capacities relates mainly to the plants of power of the peak-load as called the turbines of gas of an open cycle and a complete loading peak of hours and decreasing of an average load generator. Generally, the load shedding opportunity cost, added peak capacities, and small use of the plans of power guide to the big costs of systems per MWh of the consumed electricity. For a long-term period, the mentioned cost is an indication of the load costs of pumps of heat. More exactly, the peak capacities' cost is an indication of big prices of electricity at a rare level of electricity. The high adaption of pumps of heat and the high shortage is led by their loads of volatility. The result is that the pumps of heat over proportionately consume the shortages and pay the related price of shortage. The analysis of the sensitivity of costs of load shed of 2000 and 500 €/MWh shows that the pumps of heat of the load cost are solid related to the mentioned assumption. This is followed by the number of hours of shortage price internally decreases and correlates inversely with the price level of shortage.

11.10 CONCLUSIONS

The optimized system based on an innovative agent was improved for satisfying the many types of requirements of consumers based on different resources of renewable energies, which are affected by many weather changes. Moreover, the mentioned effect could be available for many devices of storage to save energy, for inducing an increased consumption of the quick response of consumers, and for reducing the costs of operations. The rural construction of renewable energies is a distinguished welfare, foothold to implement a rural strategy of revitalization, the distinguished point of entry, and to build wonderful villages. For considering rural and green energies' improvement—wonderful rustic construction, rustic sanitation, ecological protection of the environment, promoting the rustic development of renewable energies as a strategic policy for the sustainable improvement of rustic and agricultural areas—rustic strategies of revitalization and tap of improvement of rustic renewable

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energies potential are implemented. A flexible network of renewable energies known as the sharing network of interactive renewable energies-vehicles-buildings energies was controlled via a centralized controller of collaboration for renewable energies and the grid of electricity in response to both the demands of renewable energies and consumption of mobility of buildings' coverages. It was an investigation of the optimum management of renewable energies and sizing strategies for designing 100% microgrids based on renewable energies. The results of forecasting were utilized to improve program effectiveness and planning. There was a reduction in total costs with regard to the whole investments from 41.32% to 34.31%. Energy transition represents one of the key social challenges and economics for the coming generation to achieve environmental targets for society cost. Finally, the contribution of competition policy to achieve climate and environmental goals is mentioned. The power sector economics under VRE high penetration can be estimated properly with CRL that determines the power storage requirements with high VRE penetration and illustrates those simple analyses using the CRL to reproduce detailed modeling results reasonably well. The farms of wind could be economically fertile and viable if their values of electricity were more than their traditional costs, and the pumps of heat will be cost-efficient if their costs of load plus the whole costs of alternative technologies of heating outperform investments. Further research is required introduce the concept of heat pump load cost and observe substitution effects between different flexibility options.

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CHAPTER

12 RENEWABLE ENERGY AND PRIVATIZATION

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Maulidia, M., "Renewable energy and privatization," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 12-1–12-18.

12.1 INTRODUCTION

Electricity sectors around the world are reforming in an effort to ensure excellent quality of service, reliability, and affordable prices. These reforms have not always considered the need for decarbonization, an important consideration in light of the 2015 Paris Agreement. While not environmentally focused, the economic success of reforms in developed countries during the 1980s and 1990s has influenced emerging economies to adopt similar actions. However, the results of these reforms have been far from ideal (Bacon and Besant-Jones, 2001), mostly because emerging economies have under-developed markets, weak institutions, and unstable political structures (Sen *et al.*, 2018).

More recently, many Asian countries have undertaken their own electricity sector reforms in an effort to address electricity shortages and grow their own economies (Sen *et al.*, 2018). However, with most of these countries juggling the need to meet basic access requirements, distributional fairness, and environmental objectives, such efforts at reform have been less than effective (Sen *et al.*, 2018). One reason for this has been the presence of single vertically integrated utilities, which create a natural monopoly with strong state control (Joskow, 2008). Most often, these concentrate power in a single entity that rarely possesses the required financial, technological, and institutional competence to implement such a transition. Such government entities—with responsibility for the whole of the electricity supply chain, while also acting as the single off-taker from IPPs—often operate with inherent conflicts of interest. This is especially so in the absence of an independent regulator, where the entities themselves end up acting as a *de facto* regulator, which compounds the problem because the entity naturally works to protect its own interests. This state of play has been a major challenge for Indonesia's electricity market reform.

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This article seeks to fill a gap in studies on Indonesia's current efforts to reform its electricity sector after the repeal of the Law of Electricity No. 20 Year 2002 in 2004 that mandated a fully competitive market system. The current monopolistic system in Indonesia is inefficient; a more competitive market should go hand in hand with decarbonization. Through an analysis of interviews with decision-making stakeholders in Indonesia, this article highlights the barriers to RE investment and deployment in Indonesia and tries to analyze the link of institutional and market reforms with greening the electricity sector.

12.2 ELECTRICITY SECTOR REFORM AND THE NEED FOR DECARBONIZATION

Frustration over the unsatisfactory performance of state-owned utilities has been the main driver of most developing countries to commence an electricity sector reform (Besant-Jones, 2006). The main response has been to scale-up new investments to meet the rapidly growing demands for electricity amidst fiscal pressure, while at the same time safeguarding the poor (Besant-Jones, 2006). Jamasb *et al.* (2017) suggest that a successful reform not only brings about economic benefits but also helps to alleviate poverty by providing electricity access (Jamasb *et al.*, 2017). Competition is not usually the ultimate goal of such reform but rather governance frameworks that benefit the consumers (Joskow, 2006). Each country will implement its own unique path depending on a range of conditions (Besant-Jones, 2006).

While the electricity supply industry worldwide began with natural monopolies due to the high investment required and their ultimate contribution to social welfare (Toba, 2007), over time, this industry potentially performs better in a competitive market with multiple players (Toba, 2007). This is because private firms have higher productive efficiency compared to public utilities. Therefore, a market reform usually takes place at the time of privatization (Pollitt, 1995).

Although privatization is important, a market reform is not merely about the transfer of ownership; it is highly context and industry-specific (Pollitt, 1995). Empirical studies demonstrate private firms' higher performance. However, it is the institutional changes of private ownership, not the issue of ownership itself, that affects efficiency and social welfare (Toba, 2007).

From the experiences of electricity sector reforms in the OECD countries, it is clear that a "blueprint" for successful reform will include: Involvement of IPPs, corporatization of state-owned utilities, enactment of electricity legislation, establishment of an independent electricity regulator, unbundling of vertically integrated utilities, and privatization of the unbundled utilities (Sen *et al.*, 2018). This model works well in functioning markets, where there is strong institutional capacity and a stable political climate (Sen *et al.*, 2018), but it raises a question for Indonesia as to whether it should follow the exact steps; particularly, as it is not clear whether Indonesia has the necessary institutional structures and capabilities to implement such a reform. Throughout the country's history, liberalization is a delicate issue and avoided in public debate.

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12.3 BACKGROUND TO INDONESIA'S ATTEMPTS AT ELECTRICITY SECTOR MARKET REFORM

Indonesia's electricity sector is characterized by a monopolistic market, controlled by the state-owned electricity company, Perusahaan Listrik Negara (PLN). The Constitution of 1945 mandated the monopoly practice of PLN. At the same time, Indonesia's Law on Electricity No. 30 Year 2009 dictates that the electricity tariff is set by the government. For many years, Indonesia's decision makers have viewed their electricity consumers as entities with weak purchasing power who can only afford electricity if it is subsidized. Despite the sacrosanct nature of this practice, in 2015, the current Indonesian administration has cut the fuel subsidy and has been successful in minimizing the budget deficit.

The presence of such a rigidly regulated and subsidized electricity tariff not only prevents the market to be open and attractive for private companies, but also restricts PLN's flexibility in buying electricity from private developers. The presence of a monopoly business creates a large power imbalance that forces private developers to undergo long tariff negotiations with PLN, who as the single buyer has a much stronger bargaining position. While it has still been acceptable for some private developers with a long-term presence in the country to strike a deal, mainly because they have the strong capital to mitigate the risks while benefitting from being the first mover overall, this has deterred new entrants in the market.

Indonesia took additional steps toward the electricity sector reform by revising the Law on Electricity No. 15 Year 1985 and issuing the Law on Electricity No. 20 Year 2002. The 2002 law proposed a market-mechanism that followed some of the World Bank's measures on electricity reform, in particular, the unbundling of vertically integrated utilities and the deregulation of the wholesale market. However, some groups viewed the law as too aggressive and against Article 33[1] of the Constitution, and so the Constitutional Court overruled it in 2004. In 2009, the new law on Electricity No. 30 Year 2009 reaffirmed the State's strong control of the overall value chain of the electricity business with a few articles on unbundling and competition. According to the new law, PLN lost its legal monopoly rights but retains the right of first refusal, which leaves the private sector with less commercially attractive projects (Tharakan, 2015). In December 2016, the Constitutional Court overruled three articles of the 2009 law on unbundling and competition. The political and legal battle that undermined efforts toward market-oriented reform makes Indonesia seem reluctant to propose another reform that is stigmatized as being too "liberal." As a result, to date, Indonesia has maintained PLN's monopoly position, but this fails to encourage the necessary decarbonization required to transition away from traditional fossil fuel sources.

[1] Paragraph 3: "Earth, water, and natural resources contained are *controlled by the state* and *used for the biggest prosperity of the people.*"

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12.4 INDONESIA AND THE CHALLENGE OF DECARBONIZING ITS ELECTRICITY SECTOR

Indonesia has a relatively large power system of 43 856.58 MW of total installed capacity and 270 976 GWh of electricity production in 2019 (Perusahaan Listrik Negara, Statistik PLN, 2019, 2020). With an estimated population of 261 891 000, Indonesia's electric power consumption per capita in 2019 is 1084 kWh (Perusahaan Listrik Negara, Statistik PLN, 2019, 2020). This figure is the average of imbalance proportion between Java and non-Java. While Indonesia has improved its electrification ratio from 88.3% in 2015 to 98.93% in 2019 (Ministry of Energy and Mineral Resources, 2020a), system reliability remains a major problem. The seemingly high electrification ratio is also overestimated by the inclusion of failed government projects (Government of Indonesia and Asian Development Bank, 2015) and the solar-powered energy-efficient lamp program is considered "electrification" since 2017 (Maulidia, 2019).

Given a limited public budget, including competing priorities such as health and education, private sector investment in the electricity sector is vital, particularly, if the share of RE is to grow (Maulidia *et al.*, 2019). To achieve the renewable energy target (RET) of 23% of the primary energy mix by 2025, the MEMR estimates the need for between US$107 and US$110 billion to be invested in the electricity infrastructure over 10 years until 2025 (Ministry of Energy and Mineral Resources, 2016). PLN can only provide around 30% of that figure, which creates the expectation that the private sector will fill the investment gap (Ministry of Energy and Mineral Resources, 2016). However, the current policy landscape does not favor investment in RE.

A market reform, a move to reduce the government's role, does require a good regulatory regime (Joskow, 2006). Providing access to the poor, including pricing and subsidies, remains an important element of public and social policy (Jamasb and Nepal, 2015). While market liberalization can limit the government's direct intervention, including support mechanisms for RE (Todoc, 2006), a strong RE policy is required to minimize environmental impacts. Theoretically, the market reform will result in more productive efficiency, preferring gas in the short-term and coal in the long-term due to its low capital costs and short lead times (Todoc, 2006). In emerging economies, market reforms resulted in declining greenhouse gas (GHG) emissions per capita when an emissions' reduction policy was also present (Nepal *et al.*, 2017). A study of 55 countries showed that market reforms resulted in a decrease in private investment and lower GHG emissions (Erdogdu, 2014). Market reforms can have either positive or negative impacts on RE development, depending on each country's unique situation (Gao *et al.*, 2018). RE development should be the foundation of energy transitions and the market liberalization can support RE by moderating intermittency (Gao *et al.*, 2018). The challenge for Indonesia now is how to implement a reform simultaneously with decarbonization efforts through RE.

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12.5 LESSONS FROM OTHER ASIAN COUNTRIES' REFORMS

Compared to other emerging economies in Asia, and Southeast Asia in particular, Indonesia's progress in RE deployment is lagging (Table 12.1). Until June 2020, Indonesia had only 146.6 MW peak of installed capacity of solar PV, far below fellow ASEAN countries. As a country having the world's largest potential geothermal resources (40%), Indonesia has overtaken the Philippines as the world's number two for installed geothermal capacity with 2120.7 MW. The average growth of RE power in Indonesia is around 500 MW/year. With such a slow growth, Indonesia has only achieved 9.15% of its RE target, still far from the aspirational target of 23% by 2025.

The reforms' checklist (Table 12.2) provides a general overview of selected countries' efforts in the electricity market reform and highlights where Indonesia stands in comparison. It provides an example

Table 12.1

RE capacity in selected Asian countries. IRENA, Renewable Energy Statistics 2020 (2020); Ministry of Energy and Mineral Resources (2020b).

RE source/capacity (MW)	Indonesia	Malaysia	Thailand	The Philippines	India	China	Japan
Geothermal	2131	…	…	1928	…	27.78	
Hydropower	6096	6245	3667	3760	50 225	356 403	50 008
Bioenergy	1890 (biomass and biogas)	919	4258	393	10 228	16 537	3197
Solar PV	146.6 MWp	882	2987	922	35 060	205 493	61 840
Wind	154.3	…	1507	427	37 505	210 478	3786

Table 12.2

Electricity reforms checklist OECD 2013. Adapted from Sen *et al*. (2016).

Country	Independent power producers	Independent regulator	Unbundling	Corporatization	Open/ third-party access	Distribution privatization
Indonesia	x	No	No	x	No	No
India	x	x	x	x	x	x
Malaysia	x	x	x	x	No	No
Thailand	x	x	x	x	x	No
The Philippines	x	x	x	x	x	x
Japan	x	x	x	x	x	x

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of how reform can go hand in hand with decarbonization. Thailand and the Philippines provide appropriate benchmarks for Indonesia due to their similar economic development status, while Japan is a unique case because its move toward liberalization started more recently in 2013.

12.6 DATA AND METHODS

12.6.1 Data collection and sources

The data used for this article are primary and secondary data collected through interviews and the document analysis. To better understand Indonesia's approach for incorporating RE into their electricity sector reform, 22 in-depth interviews were undertaken with 31 participants; all were asked the same set of questions. All interviews were recorded and subsequently transcribed. The study design has included 30 potential participants representing the private sector, government, financial institution, and academia and think-thank. Two of them held positions as ministers and one was the former CEO of PLN. The inclusion criteria for selecting participants included that they held a decision-making position in their respective organizations and had expertise in RE policy in Indonesia. The participants' responses were coded using simple coding of P (private companies), G (government) N (NGO) with the one bank representative also coded "N."

The number was chosen based on the preliminary interviews with similar stakeholders 1 year earlier. It was expected that beyond 30 participants, data saturation would be reached. The study design also included 10 additional participants as a backup if data saturation could not be achieved with the first 30 participants. Data saturation is the point where data collection provides enough information to replicate the study (O'Reilly and Parker, 2013), is able to generate new information (Guest *et al.*, 2006), and does not generate new themes, codes, and data (Guest *et al.*, 2006).

To check whether data saturation had been achieved, a manual coding analysis was performed after the first ten interviews have been done. Beyond 15 interviews, the analysis generated no new code; hence, no new theme/data. To ensure the consistency of the themes, a triangulation using Leximancer software was done. The result shows that the themes generated from manual coding were consistent with those generated through software in terms of both frequency and co-occurrence.

12.6.2 Qualitative content analysis

A qualitative approach was deemed the most suitable for exploring the barriers to RE deployment in Indonesia as it is a phenomenon with unique complexities and anomalies. A qualitative analysis allows the researcher to be better able to capture the social meaning and experiences of the participants (Hammarberg *et al.*, 2016). Content analysis is also a useful method for undertaking case study research

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because its systematic procedures and rule-based systems help to deal with complexities in interpreting the context and evidence provided through interviews (Kohlbacher, 2006).

Triangulation is useful to increase the depth of knowledge and to achieve better understanding through different perspectives. It cross-validates the results and provides a more thorough text analysis (Renz *et al.*, 2018). A computerized text analysis tool, Leximancer, was applied. Emergent concepts are drawn out based on frequency and co-occurrence (Smith and Humphreys, 2006; and Cretchley *et al.*, 2010). Leximancer validates the manual coding and enables an exploratory approach and presents a visual analysis through concept maps.

12.7 RESULTS AND DISCUSSION

PLN[2] arose as a major theme across all datasets. PLN as a theme, not as a corporation, is seen as the biggest obstacle to private investment in RE in the country. Most participants understand that PLN should not be held accountable for the complicated governance, but rather the country's law puts them in an onerous position, as such participants mentioned PLN as one of the major barriers to RE development. Other cross-cutting themes that emerged included institutional competence ($n = 11$), tariffs ($n = 11$), FITs ($n = 10$), policy/regulations ($n = 7$), monopoly ($n = 6$), technical and financial competence ($n = 9$), politics/power ($n = 7$), commitment ($n = 3$), and corruption/fraud/patronage ($n = 2$), and these are summarized below.

Based on the content analysis, several factors were identified as barriers to RE development and achieving the RET in Indonesia. The barriers can be classified into three key areas: government/policy, corporate issues, and project issues.

12.7.1 PLN's obsolete business model amidst a populist subsidy policy

The ministerial decree stipulates that the new purchase price uses the main production cost of electricity (BPP)[3] as the benchmark. This sparked criticisms as BPP fluctuates over time and does not denote the levelized cost of electricity. Hence, BPP is not an appropriate standard for determining tariffs. The policy was also determined unilaterally without proper consultation with the affected RE private developers. The disappointment of the practice of making policy in seclusion was expressed by one of the geothermal developers as "a nail in the coffin for RE (P8)." Private investors view this regulation as a disincentive for RE. PLN, yet on the other hand, praised the regulation for its compatibility with

[2] PLN (*Perusahaan Listrik Negara*), a state-owned electricity company that monopolizes the whole chain of electricity business (generation, transmission, distribution, and wholesale) in Indonesia.

[3] *Biaya Pokok Produksi*—Main cost of electricity production.

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PLN's financial capability (G5). By the time this article is written (2020), a Presidential Regulation on purchase price from RE is being drafted.

12.7.1.1 Institutional competence

The new MEMR decree on RE sources was issued in January 2017, replacing several FIT regulations for different RE technologies, which had mostly been in effect from 2015 to 2016. This regulation (now revoked) dictated PLN to buy electricity from RES at higher tariffs. After the issuance of FITs for micro-hydro in 2015, PLN openly challenged the then Minister of Energy of not obeying the rules because the subsidy for the price gap was not provided by the government. Paying higher tariffs for RE would have caused PLN to get into financial difficulty (Agustinus and Idris, 2015; and Agustinus, 2016). Seven participants believed that PLN's insufficient institutional competence hampered the efforts to achieve the RET (G1, G2, N4, N7, P1, P2, and P8).

G1 mentioned that

"PLN acted on its own will. At the same time, the government was powerless and could not enforce its own policy."

P1 agreed that

"The Minister of Energy could not influence PLN on RE decisions."

G2 criticized PLN's lack of understanding of RE as the main barrier to RE deployment in the country. This view was supported by other participants (P1, P8, and G2), who suggested that RE was not high on PLN's priority list since it was not included in PLN's key performance indicators (KPI) determined by the Ministry of State-owned Enterprises (MSOE).

A broader observation on the lack of harmony among government institutions, including PLN, was provided by an NGO (N4). It needs to be acknowledged that PLN is in a difficult situation with such a big mandate in the way Indonesia's electricity sector is governed (N7, P1, P2, and P8). The monopolistic structure of PLN leads to a conflict of interest of PLN as a generator and a buyer of IPP's product, while also having fiscal responsibility to the nation. The decision-making process within PLN was also criticized as being too dependent on one person with a clear absence of standardized criteria for decision making (P2).

12.7.1.2 Non-binding policy/regulations and absence of a strict emissions standard

PLN's refusal to respect the MEMR decree on FITs did not have any consequences because PLN reports to the MSOE instead of to the MEMR. The absence of mechanisms to compensate for the price gap between the premium FITs and normal tariffs was mentioned by seven participants as a critical factor

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that made PLN reluctant to buy electricity from RE IPPs (P1, P2, P3, P5, P8, N7, and N9). FITs were regulated only at a Minister decree level, were seen to have a weak legal basis, and were not mandatory for PLN to follow (N4, P1, and P3). Therefore, the Law on Renewable Energy had to be in place to ensure the clarity of the mandate and sanctions (N4). Since the future of the electricity supply is in the hands of the private sector, the current regulatory framework revolves around PLN and needs to shift to more private/community oriented (N5). Such a change in the regulatory framework, however, has to be complemented with behavioral change (N5). This view was also supported by P2 who stated that the absence of a policy breakthrough to change PLN was an obstacle to RE development, and the RET was not legally binding to PLN.

One of the reasons why coal remains preferable for PLN is the absence of emission standards for coal/diesel power plants in Indonesia (G1, G4, and P1). Without recognition of the health and environmental costs caused by fossil fuels, it was thought that it would be difficult for RE sources to compete. Indonesia's emission standards are among the weakest in the world and not enforced (Bhati *et al.*, 2017). The new standards issued in 2019 are 4–16 times weaker than those applied in China and their enforcement is weak. Some view an energy resilient fund (DKE) coupled with a coal tax as a useful mechanism to create a level playing field; however, they also expressed doubt as to whether the government would be courageous to put pressure on the fossil fuel industry (G1, G2, G4, and P8).

12.7.1.3 Monopoly

Six participants asserted that the monopoly of PLN had hampered RE development in Indonesia. PLN as the single buyer of electricity gave IPPs no choice but to follow PLN's terms and conditions, which always favored PLN's own interests (G2 and P2). Ideally, to achieve productive efficiency, it was felt that the market should be deregulated to adopt a multi-seller/multi-buyer system (G2 and P2),

> "That's why we're being left behind compared to Malaysia, to other countries. They have started to unbundle." (G1)

It was also acknowledged that being responsible for the whole value chain of electricity supply in the country placed an overwhelming burden on a single entity. One participant suggested that at least one of the functions, for example, transmission, could be contracted out (N2). It was thought that PLN's monopolistic behavior and corporate culture would always orientate toward large-scale generators mostly coal and gas-fired power (N5 and P2) and tend to exercise its power (N5). This behavior works against supporting RE sources of electricity in Indonesia that are usually small scale, except large hydro- and geothermal.

The absence of vertical unbundling of PLN was also thought to make PLN slow and inefficient (G1, G2, N5, N6, and P2), which indirectly made the RE market difficult to grow. N5 was pessimistic that the unbundling of PLN and a more liberalized market would happen because it had been three decades since the first effort was undertaken in the late 1990s during his service. Finally, PLN's role as monopoly

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holders made it difficult for RE IPPs because PLN naturally works to protect its own base. However, it was noted that PLN could influence the MEMR's decisions on electricity concessions for off-grid RE IPPs (P1) and that privatization of some of PLN's functions may benefit the electricity sector, at least in the beginning through the sale of the overvalued PLN's assets (P1).

12.7.1.4 Tariffs

PLN's limitations stem from the government-regulated end-consumer electricity tariffs that make PLN not to even have influence over its own revenue. This causes PLN's inflexibility in negotiating with IPPs. PLN felt that the rigid tariff scheme forced them to pay for the fluctuating electricity tariff, which is calculated based on the exchange rate, inflation rate, oil, and coal prices[4] (G5). In addition, the absence of a cost of service or price cap regulation causes PLN to negotiate power purchase agreements (PPAs) with IPPs individually (N2). Since the tariffs do not reflect the actual cost of production, PLN is in a challenging position when dealing with IPPs (P2). The IPPs demand cost-reflective prices while PLN is bound to government-set tariffs. The current administration's electricity subsidy restructuring program puts a cap on the subsidy PLN offered each year. Obviously, the "take or pay" clause in PPA increases the market demand and places a price risk on PLN (G5), and subsequently, prudent risk assessments and bureaucratic coordination prolong the negotiation with IPPs. The private sector believes that the long process of PPA tariff negotiations with PLN is the biggest obstacle for RE development (N2, P2, P3, P4, P5, P6, and P8). It was also felt that PLN's higher bargaining power tended to place further pressure on developers (P3) as PLN could not guarantee they would agree to the tariffs after project developers had already made an initial investment (N6).

12.7.1.5 Politics/power

The Constitution mandates PLN to monopolize the electricity sector and to provide affordable electricity to the people. PLN's centralized structure and bureaucratic decision-making reflect how the whole electricity sector is governed. Each year, PLN needs to offset its loss from lower consumer tariffs by relying on government subsidies. This dependency makes PLN susceptible to the political deliberations of the parliament.

A major barrier to RE development is the absence of a common vision among political leaders at the national, sectoral, and corporate levels (G1). In cases involving RE decisions, PLN was seen to have a major influence in political decisions (P1). One interviewee suggested its power stretched beyond its roles and responsibilities (P2), and at times, because of its influence on MEMR, PLN actively resists policy implementation (P1 and P7). In the case of FIT regulations, the stakeholders observed obvious

[4] According to MEMR's Decree No. 28. Year 2016 on Electricity Tariff Provided by PLN, MEMR may adjust electricity tariffs once every 3 months taking into account the fluctuating exchange rate against USD, Indonesia crude price, inflation rate, and coal benchmark price. However, since 2017, the tariffs have never been adjusted/increased.

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political battles between PLN and MEMR under the leadership of the previous Minister (P2), which resulted in them refusing some applications for off-grid electricity concessions (P7).

12.7.1.6 Technical and financial competence

Some private developers viewed PLN's lack of technical competence in dealing with IPPs as a key hindrance to RE development. This included a lack of capability in preparing requests for proposals (P1) and a lack of capacity to provide reliable, transparent, and grid data (P2). The private developers also questioned PLN's grid model quality and the absence of clear procedures or criteria for connecting to PLN's grid, comparable to Australia's National Electricity Rules (P2). Another observation highlighted the lack of competence of both MEMR and PLN in planning. In particular, for off-grid electrification efforts, it was noted that PLN does not have a national least-cost plan, which is an important tool for ensuring program effectiveness and transparency (P7). It was also noted that PLN does not have systematic criteria in determining WUK[5] decisions (P7).

PLN fails to realize its limited financial capability and that it has to rely on the private sector to build the electricity infrastructure (N4 and P3). On the other hand, in securing finance from investors, project developers are required to involve PLN to minimize risks (N6). PLN's annual revenue from the low government-set tariffs is always less than its operating expenses (Table 12.3); therefore, without government subsidies, PLN suffers huge losses. Losses from differences in the foreign exchange rate

Table 12.3
PLN's financial statements 2010–2020.[a] Perusahaan Listrik Negara, Statistik PLN 2019 (2020).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Revenues before subsidy	7.36	8.11	9.13	11.34	13.65	15.34	15.73	18.02	19.26	20.16
Operating expenses	10.53	13.65	14.34	15.60	17.43	15.92	17.96	19.45	21.76	22.69
Profit/loss before subsidies	−3.17	−5.55	−5.21	−4.25	−3.78	−0.58	−2.23	−1.42	−2.49	−2.10
Government subsidies	4.10	6.58	7.29	7.14	7.01	3.99	4.10	3.23	3.34	3.65
Net financial/foreign exchange rate difference	−0.13	−0.48	−2.01	−5.35	−2.11	−4.54	−0.91	−1.20	−0.77	+0.67
Profit/loss for the year	0.71	0.51	0.23	−1.85	0.83	0.43	0.58	0.31	0.82	0.30
Basic earning/loss per share (in US$)	15.4	11.0	4.9	−40.1	17.9	9.2	10.6	3.6	7.4	2.65

[a] *In billion U.S.$* * assuming fixed exchange rate of IDR 14 165/1 U.S.$.

[5] *Wilayah Usaha Ketenagalistrikan* or Electricity Business Concessions, rights given to private companies, cooperatives or communities to generate, transmit, and distribute electricity in an administrative area, regulate by MEMR Decree No. 38/2016 on The Acceleration of Undeveloped, Remote, Borderline Villages, and Populated Small-Islands Electrification through the Implementation of Small-Scale Electricity Supplies.

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also exacerbate the problem. Table 12.3 shows that in 2013, despite huge subsidies of U.S.$ 7.14 billion, PLN still has a negative balance, and historically, PLN has always remained in a state of insolvency.

12.7.1.7 Commitment

A lack of commitment to RE is stated as one of the major obstacles to its deployment. Since PLN reports to the MSOEs, the commitment needs to come from this Ministry as the one that mandates PLN to be profitable (G2). PLN also lacks an RE focus and is currently tasked to build a large-scale infrastructure through the 35 000 MW program as well as upgrades to transmission and distribution systems. It is safe to say that PLN has no intention or incentives to develop RE and still relies on coal (P2).

12.7.1.8 Corruption/fraud/patronage

Interviewees suggested that the energy sector in Indonesia has some governance issues. Power abuse, corruption, and greed are terms that were proffered throughout, and this has also been acknowledged in more recent literature, which observes that the corrupt political-economic environment puts PLN in a difficult situation to maintain their integrity (Van Eeden Jones and Lasthuizen, 2018).

12.7.2 Triangulation

The analysis using Leximancer software confirmed and added more information to the manual coding results. The results from the analysis of the private participants are mostly consistent with the results from manual coding (Fig. 12.1). The most important theme, as indicated by color red is PLN. PLN is mostly associated with price, tariff, and subsidy. The private sector views that the biggest challenge in RE is to secure a PPA at a price that is acceptable for both parties. The fact that PLN depends heavily on government subsidies each year makes them reluctant to proceed with IPP, especially RE, because it does not have control over its own funding. However, some of the participants realize that PLN should not be held accountable for the high price of RE (P2 and P8). Instead, it was felt that there has to be a mechanism like a subsidy for RE, which could be obtained either through the establishment of a trust fund or additional taxes and charges for fossil fuel usage to pay for the price gap.

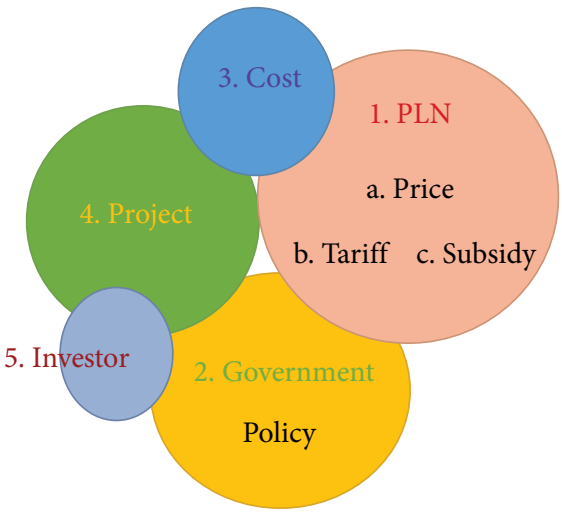

FIG. 12.1
Concept map of barriers to renewable energy in Indonesia expressed by private sector participants. *Redrawn from Leximancer for more clarity.*

The second most important theme is government. Most participants criticized the government's lack of commitment to RE despite its announcement of an

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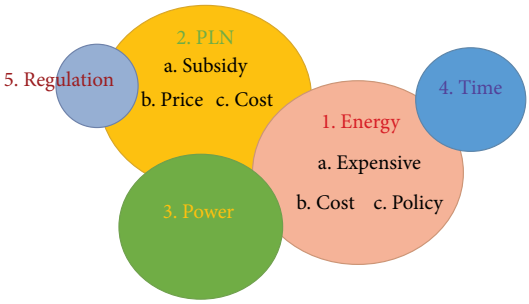

FIG. 12.2
Concept map of barriers to renewable energy expressed by Indonesian government participants. *Redrawn from Leximancer for more clarity*.

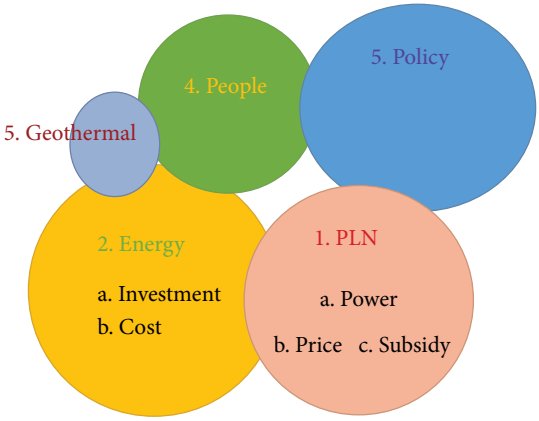

FIG. 12.3
Concept map barriers to renewable energy expressed by NGO participants. *Redrawn from Leximancer for more clarity*.

emissions' reduction target and RET. The government's commitment to achieve equality through electrification of the most remote areas is also being questioned.

Slightly different from private participants, government participants' concerns centered around the debate between affordability vs sustainability of energy. This covered the concepts of electricity, people, need, means, sector, cost, and expense (Fig. 12.2). Three participants agreed that the government should issue a policy that gives affirmative action for RE (G1, G2, and G4) and takes into account the real cost of coal (G4). Meanwhile, G3 insisted that cheap energy should take precedence over more expensive RE. Another (G5) was of the opinion that PLN and the government must adhere to the principles of no trade-off between affordability and sustainability. G5 suggests the need to build RE to co-exist with coal.

NGO participants also agree that the current subsidy and tariff policies make it difficult for PLN to adopt RE (Fig. 12.3). They felt that a Law on Renewable Energy is a prerequisite (N4), such a matter of high importance, should be administered through government regulations at least (N5). These participants felt that focusing only on structural change is insufficient and that PLN and the government should embrace both new regulatory frameworks and behavioral change simultaneously (N5).

Finally, when combining all interviews, the most important theme that emerged, as indicated by color red is *PLN*, followed by *government, power, energy, regulation and Minister* (Fig. 12.4):

"The way PLN is structured is the main obstacle. The fact is there is no market here is the bigger issue." (P2)

The change in the mechanism of the government subsidy to PLN affects its ability to afford the higher price of RE-sourced electricity. The current subsidy is calculated based only on the government-set consumer tariffs, which means that PLN has no additional financial resources to cross-subsidize RE. The Ministerial decree No. 50 Year 2017 on the price of RE is, therefore, more compatible with PLN's interest (G5):

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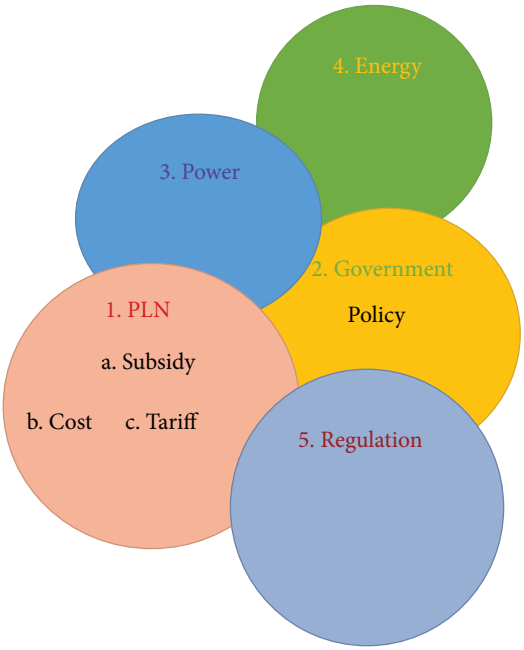

FIG. 12.4
Concept map barriers to renewable energy aggregated across all participants. *Redrawn from Leximancer for more clarity.*

> "So at that time, PLN was asked to blend the cost. Bear in mind that when the cost is blended, the electricity tariff is capped, it is regulated by the government politically." (G5).

The challenge for private developers remains how to compete, given this limitation to PLN:

> "In this current environment where PLN has so much power and has an interest in their finances, the private developers need to make our business plan work for them as well." (P2).

From the analysis of interviews, most participants view PLN as a separate entity, independent of the government and which seems to have even more power and influence than the MEMR. Some are concerned by the lack of commitment from the government and its lack of ability to enforce its own regulations within an SOE. PLN reports to the MSOE. This situation makes it difficult for the MEMR to impose any regulations, notably in relation to RE, that will threaten PLN's status quo. The FIT regulations to support private investment did not work due to PLN's resistance. Nevertheless, the regulation does not clearly state where the fund to provide a premium price of RE comes from. The structure, business model, and regulatory framework into which PLN is embedded exacerbate the challenge of increasing the investment in RE.

There are many cross-cutting themes that are intertwined and create a complicated policy and political web that needs to be resolved. The most prominent themes include institutional competence, commitment, financial capability, power and politics, subsidies, and tariffs. A lack of commitment and vision toward RE from the government not only leads to confusion among private investors, but also hampers the government's own programs such as the RET and electrification of remote villages.

Both PLN and the government are rigid and very slow in responding to a new era dependent on clean and sustainable energy. RE growth in Indonesia requires changes that need to move beyond a structural change in PLN and the government. The current regulatory framework and the old mechanisms are no longer suitable to promote RE that has very different characteristics from large, polluting power plants. Complete and thorough structural, regulatory, and market reforms are the foundation for successful reforms as seen in England and Wales (Joskow, 2006).

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Indonesia has yet to establish an independent regulatory body. Such an entity could become responsible for issuing market rules, unbundling supply and distribution value chains, and opening the wholesale market for competition. However, with the current politicized nature of energy and PLN ownership, there are many political battles ahead to make such reforms successful.

12.8 CONCLUSIONS

This article contributes to the ongoing discourse regarding the current challenges of decarbonizing the electricity sector through RE concurrently with implementing market-based reforms in an emerging economy context. With a focus on Indonesia, it is revealed that the PLN's structure, business model, and regulatory framework exacerbate the challenges for RE investment by the private sector, which is necessary if decarbonization goals are to be met. Analysis revealed that any RE policy that is favorable for PLN is typically not friendly toward private investors. Conversely, FIT support mechanisms, normally a helpful mechanism for progressing structural change, are seen to burden PLN. While private investors would gain benefits from such a reform, there is also an opportunity for PLN to restructure its business model, moving away from dependence on government subsidies. However, this is unlikely to occur without increasing the costs of electricity supply, which has implications for broader Indonesian society, where currently many in remote areas do not even have the luxury of reliable access. Based on the findings from this research, simply scaling up new investment appears to be insufficient to drive politicians and policymakers to commit to institutional and market reform. While other countries' reforms were driven by both political ideology and economic efficiency (Sen *et al.*, 2018), these are missing drivers within Indonesia's current energy sector political economy. The interviews reveal that PLN is vulnerable to any changes in the status quo, including the government's own subsidy restructuring program, as it threatens PLN's financial solvency. This should provide a warning to the current administration to implement actions that can reform PLN and the electricity sector. Furthermore, there is growing public scrutiny of PLN based on corruption allegations. To prevent such scandals in the future, fundamental changes to the way the electricity sector is governed are required. The establishment of an independent regulator and unbundling of PLN should be the first steps to promote competition and devolve PLN's dominance over such a vital and strategic, essential service. The independent regulator could then develop transparent electricity industry codes and market rules. It is recognized that political commitment is the first and foremost requirement of a reform (Besant-Jones, 2006). Legal and regulatory framework reform could commence with the revision of the Law on Electricity and the currently drafted Law on Renewable Energy. Indonesia's competency in law making is critical to ensure the development of a framework for reform that can be implemented. Lessons learned from other countries show that market reforms need to be combined with a strong RE policy to achieve decarbonization objectives. This should include FITs, the subsidy mechanisms, and funds similar to DKE proposed by the previous Minister of Energy. The important decisions in integrating more RE are mechanisms for paying the difference between FITs and the

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benchmark price. These constituted highly political decisions and will be dependent on whether the government is courageous enough to pass on the costs to consumers or to find alternative financing sources, such as placing additional charges on fossil fuel usage. External factors can drive Indonesia's electricity sector to change. With the advancement of technology leading to the continued drop in the price of RE, notably solar and wind, the world is facing greater disruption to the status quo of how electricity is generated. With such advancements, the inert business model of PLN prevents it from being able to respond to a more competitive market. Unless policymakers move away from Indonesia's reliance on fossil fuel generation and subsidies to provide greater public benefit, PLN faces far more serious financial problems. The discussion on tariffs should move forward in the direction of price-cap regulation and demand response programs that would enable PLN to give appropriate incentives to then change customer behavior. The discussion on tariff increase shall no longer be considered taboo. Ideally, tariffs should enable PLN to recover their investment and include a possible surcharge for RE. This study serves as a starting point for further research but experienced certain limitations. First, it focused on the barriers and challenges to RE investment in Indonesia. While an important starting point for research, deeper institutional and market aspects need to be taken into account. Second, a continuation of the study to further investigate the applicability of the proposed actions will provide more meaningful contributions to policy making in Indonesia and other emerging economies facing similar problems. Third, although this study relied upon high-profile stakeholders, the involvement of other stakeholders who are not supporting RE may have provided an alternative perspective that could enrich the study.

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CHAPTER

13 RENEWABLE ENERGY: POLITICAL AND POLICY ANALYSIS

Nadejda Komendantova

Komendantova, N., "Renewable energy: Political and policy analysis," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 13-1–13-16.

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13.1 THE DEVELOPMENT OF RENEWABLE ENERGY: SKEPTICISM, RELUCTANCE, AND INABILITY

The deployment of renewable energy sources (RESs) is beneficial for several arenas such as climate change mitigation and energy security. Solar power, wind, biomass, and other RESs help to decarbonize the energy sector while generating low carbon energy. Several countries have set targets for the deployment of RESs to reach their commitments under climate change agreements.

RESs are beneficial for energy security because they help to satisfy the existing and potentially growing demand for energy with locally available sources. Several countries have set targets to satisfy their domestic energy demand and reduce energy imports. As a way of promoting energy security, the RES has been examined for its technical feasibility (Streicher *et al.*, 2010) and impact on the demand for local goods and services, and in turn, labor (Berndes and Hansson, 2007; and Müller *et al.*, 2011) and tourism (Jiricka *et al.*, 2010). Recent scientific papers have focused on the integrated assessments of the deployment of renewable energy, as it contributes to not only climate change mitigation, but also energy security and socioeconomic development.

More than 80% of today's energy industry is based on nonrenewable sources—oil, gas, coal, nuclear energy, and so on. However, given the declining global reserves of fossil fuels and the need for future energy security and independence, the trend toward the increased use of renewables has been growing worldwide in recent decades. More than 50 countries have identified the energy sector—the green energy industry—as a priority and support the development of RES.

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Several terms are used in energy policy when speaking about the deployment of RES. These include "energy transition" and "transformation of energy systems." The terms "green economy" and "green growth" are also frequently used. An inclusive green economy is a tool for achieving sustainable development and responding to three challenges facing humanity: poverty, inequitable distribution of growing prosperity, and the exceeding of planetary boundaries. Green growth involves stimulating economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being depends. Green jobs, the backbone of a green economy, are provided by low-carbon industries whose primary function is to green the economy. They are one of the major drivers of social acceptance of energy transition.

There is a vast literature on energy transition, in particular, the technical opportunities and barriers (Fichter *et al.*, 2013; and Trieb *et al.*, 2014). However, scientific evidence and practical experience with social components of energy transition are much less common. A meta-analysis by Sovacool (2014), who analyzed all Scopus papers on energy transition, found that only 3% of studies dealt with the social factors of energy transition. These factors include the social and public acceptance of energy transition; willingness to use RES; willingness to pay for their deployment; attitudes toward energy transition; the heterogeneity of worldviews about the future of energy; and perceptions of the risks, costs, and benefits of various energy-generating technologies.

The failure of policymakers and decision-makers to address issues of social acceptance results in protests that delay the implementation of renewable energy projects. In some cases, public opposition even results in the cancellation of projects. Public opposition is a significant obstacle that limits the use of local renewable energy resources (Abegg, 2011; and Schmidt *et al.*, 2012). Therefore, it is crucial to better understand public acceptance by examining commitment to (and willingness to pay for) energy security coupled with climate change mitigation and regional development.

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13.2 SOCIAL FACTORS AND THE DEVELOPMENT OF ENERGY POLICY IN AUSTRIA AND JORDAN

13.2.1 Austria

Austria is one example of how energy policy is proceeding with the joint goals of energy security and climate change mitigation. Austria has an ambitious climate goal: for the RES to make up to 78% by 2050. The country, perhaps uniquely, regard energy security and regional development as co-benefits (if not the primary benefits) of the energy transition. It aims to become energy self-sufficient by 2050, primarily by investing in renewable energy and increasing energy efficiency (Climate and Energy Fund, 2014). The use of RES is also viewed as a strategy for promoting regional development.

Austria is pursuing its climate goals, and thus energy security and regional development, by supporting climate and energy model regions that are committed to becoming independent of fossil fuels by 2050.

The main instrument for this is the Austrian Climate and Energy Fund, which provides support for the deployment of renewable energy technology. Local and regional governments also provide subsidies for these technologies.

The climate and energy model region approach raises fundamental questions about the political, social, and economic feasibility of pursuing the RES on a regional scale. Because renewable energy is generally more costly than (subsidized) fossil fuels, it is prudent to begin by asking whether the Austrian model region concept is, in fact, a no-regret strategy from an economics-only perspective. How much will the added economic benefits (net across Austria) from the ensuing regional development contribute to counterbalancing the added economic costs of using RES? If significant costs remain, who will pay taxpayers through subsidies or consumers in the region? Will a commitment to Austria's threefold goals motivate consumer willingness to pay and political will to shoulder the economic burden?

The concerns are not only economic. Throughout Austria, communities are increasingly raising opposition to wind, biogas, and other technologies in their vicinity, which raises the question of how (if at all) to secure public acceptance. These and other questions underline the importance of examining the economic, political, and social feasibility of RES before similar policies are pursued throughout Austria and in other countries. The climate and energy model region approach and flagship projects offer unique insights into these and other questions.

The experience of the town of Güssing raises concerns about the economic feasibility of Austria's model region strategy. Güssing is located in Burgenland, an economically peripheral and structurally weak region. The town's approximately 30 renewable energy technologies (mainly biomass, solar power, and wind) reduce greenhouse gases, create energy security, and promote regional economic development. Its capital-intensive investments have been financed through feed-in tariffs, grants from the national and regional governments, user fees, and bank loans (Douthwaite, 2014). Today, renewable energy generated in the region fully covers the demand for electricity, with a surplus supplied to the national grid. It is estimated that by reinvesting the surplus in the region, the town has created about 1000 new jobs and 50 new companies (Koch *et al.*, 2006). However, recent research has revealed that the model was in jeopardy when subsidies for the operation of the biomass facility were withdrawn. Following this withdrawal and local elections, in which the party of the mayor (who had championed the project together with a local entrepreneur) lost popular support, it was revealed that the municipality was heavily in debt. Although it can be necessary to take on debt to finance infrastructure with high upfront costs (and resulting low operating costs), the political fallout from the revelation of the municipal debt may signal public dissatisfaction with the strategy. This stands in sharp contrast to political rhetoric that has justified investment in the RES on the basis of the multiplier effect leading to greatly increased economic activity in structurally weak regions.

The Güssing experience raises the issue of the overall costs and economic benefits (and their temporal, generational, and spatial distribution) of meeting Austria's climate, energy, and regional development goals. Past calculations of the economic benefits of regional energy autarky have proven overly

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optimistic, and public opposition to energy autarky appears to be increasing. From an economic perspective, what are the pros and cons (benefits and costs for the region and Austria) of pursuing regional energy independence with the RES? Under what conditions can it be a no-regrets strategy?

The Güssing experience also raises questions about the social and political viability of Austria's climate and energy model regions, in particular, as the Austrian government is investing heavily in 83 regions, each of which will require support from (at least) three sets of stakeholders:

- residents of the model regions, who will be called on to show support for allocating regional and municipal funds to capitalize on investments in the RES infrastructure (social acceptance);
- energy consumers in the region, who may be called on to pay higher energy prices because of high infrastructure costs (consumer willingness to pay); and
- taxpayers throughout Austria (and their political representatives), who are already being called on to subsidize the model regions (political will).

Social acceptance, consumer willingness to pay, and political will are critical for the success of the model region concept and energy transition more generally. This is not only because the public (as both taxpayers and energy consumers) will have to bear any extra costs, but also because they will have to change how energy is supplied to their communities. For example, the municipal council of Kaindorf, a town in an Austrian model region, is proposing that the municipality finance photovoltaic (PV) technology for the roof of the courthouse. This is an important symbolic step in energy transition, but one that will inevitably reduce funding for other needed municipal projects. Because the council is more likely to approve such projects in an atmosphere of public support, the Kaindorf region is investing in procedures that will improve communication and public participation (a flagship project supported by the Climate and Energy Fund). In other words, officials in Kaindorf recognize the need to address energy transition governance and are promoting transparent procedures as a key element in this process. Residents in model regions are also, in many instances, objecting to locating wind, biogas, and solar installations (in particular, energy transmission lines) in the vicinity of their communities. Research has demonstrated that public opposition to energy-generating infrastructure projects has its roots in a wide range of factors. Foremost among these are concerns about health and safety risks, the effects of the project on the local landscape and environment, and the decrease in property values that may result.

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13.2.2 Jordan

Jordan, which imports 95% of its energy, is currently struggling to satisfy its energy demand. This situation will become even more acute if the demand for primary energy continues to grow at the current rate of 7% annually. The demand for energy in Jordan will increase in the coming decades largely because of population growth, migration dynamics in the region, increased quality of life, as well as increased need for electricity for the desalination of water and cooling of buildings in response to climate change (both of which require large amounts of energy). For example, forecasts show annual

increases of 5% in Jordan's demand for primary energy and 6% in its demand for electricity by 2020 (Komendantova *et al.*, 2017). Given the lack of energy resources in Jordan, meeting demand is a constant challenge. The country is heavily dependent on the imports of energy, largely from fossil fuels. Fluctuations in energy prices increase Jordan's national debt and affect its economy.

Jordan has the potential to satisfy its growing demand for energy with locally available RES, including wind and energy. The government is also considering oil shale and nuclear power. The deployment of new technologies and greater use of existing technologies to meet the demand for energy and diversify the energy supply will lead to an energy transition in the country and a transformation of its energy system. Energy transition in Jordan will be and already is a complex process with political, social, economic, and technical dimensions. Therefore, holistic, inclusive, and comprehensive governance is essential. The process of substituting one energy source or technology for another can result in significant sociotechnical changes that might lead to friction or conflict. It can lead not only to technological change, but also to a sociotechnological transition, which will combine with changes in generation and distribution technologies, business models, governance structures, consumption patterns, values, and worldviews. For the sustainable implementation of this process, new forms of governance are needed.

The results of decision-making experiments conducted with multi-criteria optimization show that currently the discourse in Jordanian society is dominated by economic rationality (such as electricity costs) and concerns about the safe operation and maintenance of electricity-generating power plants. They also show a strong desire among all stakeholder groups to engage in decision-making on energy transition rather than to merely compensate local communities for the installation of electricity-generating and transmitting technologies.

Multi-criteria decision optimization based on the analyses of preferences of stakeholders regarding energy generation criteria shows that utility-scale PV is the most favorable technology. It was ranked as the top priority by all stakeholder groups. Also, in the final ranking with a mixed group of stakeholders, utility-scale PV was ranked at the top of the list. In individual rankings, stakeholders also ranked PV the most favorable technology. Other solar technology, such as concentrated solar power (CSP), was ranked significantly lower. The main reason for this is the high investment costs for this technology.

The discourse around energy transition in Jordan is heavily dominated by concerns about energy security. In almost all group rankings, the safety of energy generation and the affordability of electricity were ranked as top priorities. The social and environmental impacts of technologies were ranked in the middle or at the bottom. Concerns about climate change mitigation do not seem to belong to the dominant discourse, as climate change mitigation was frequently ranked at the bottom of the list. One stakeholder group, local communities, ranked global warming at the top, likely because people on the ground are feeling the direct impacts of climate change. However, in the evaluations of renewable energy technologies, the most frequent positive characteristics were "clean" and "little impact on the environment." It seems that there is a certain level of awareness of the importance of environmental protection, although there is less awareness of the risks of climate change and the need to mitigate it.

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A comparison of visions of Jordan's environmental, social, and economic future shows that young people are the most optimistic. For instance, they did not identify a single negative tendency. Among economic factors, positive expectations connected with investment in new technologies and reduced dependency on energy imports were mentioned most frequently. Positive expectations around social development were connected with the creation of employment opportunities and the generation of further knowledge. In general, there was a perception that Jordan's environmental future looks positive. Among the negative factors, a possible increase in electricity costs was named most frequently. In the social arena, stakeholders noted the destruction of traditional values and the traditional family structure. In the environmental arena, the most frequent concerns were about water scarcity.

In terms of procedural and output justice, the majority of stakeholders had an opinion that compensation for the deployment of infrastructure should be the least favorable criterion and that further efforts are necessary to facilitate the engagement of stakeholders and laypeople in decision-making on energy transition. Providing opportunities to participate in decision-making was considered the most important of four criteria of procedural and output justice.

Solar power, nuclear energy, and oil are the three energy-generating technologies most discussed in the Jordanian media. However, attitudes toward these technologies differ quite a bit. Solar power is mostly perceived positively, with PV being a top priority. CSP does not enjoy the same high level of support as PV. Nuclear energy was often considered the second or third most favorable technology. However, opinions are very polarized, and several stakeholders are strongly against nuclear power. Although oil is discussed frequently in the media, it is considered the least favorable technology by all stakeholder groups. Shale oil is considered to be much more positive, mainly because of its availability in Jordan and the aspirations for technology transfer and impulses for socioeconomic development that are connected with the deployment of this technology.

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13.3 POLICY DEVELOPMENT AND METHODOLOGIES OF BEHAVIORAL ECONOMICS

Energy transition based on the deployment of RES is a wicked process, which means that it involves a variety of stakeholders with different views and interests. Decision-making around energy transition and the implementation of energy policy at various levels of governance are influenced by the broad diversity among stakeholders and require compromise solutions. The actions and diverse perspectives of stakeholders influence the deployment of renewable energy technology and shape energy transition. Furthermore, energy transition at scale can result in profound transformations in the ways in which society deals with the generation, transmission, and distribution of energy.

Energy transition and the transformation of energy systems require technological capacity, economic incentives, and the political will to drive them. But, they also require behavioral change among the users of this technology. Energy policies to stimulate the required behavioral change should be based

on an understanding of the human factors involved in energy transition, such as the social acceptance of renewable energy technologies or willingness to use renewable energies and to engage in decision-making processes. However, the current research on energy transition focuses mainly on technical and economic factors. Only 3% of published studies address the human factors associated with energy transition.

This chapter summarizes the results of around 10 years of study in many developed, transition economies, and developing countries. The major focus of this study was the transition to greater use of RES to achieve climate change mitigation and energy security. The research questions were connected with human reasoning and behavioral factors such as perceptions of the risks and benefits of the RES, views on top-down and bottom-up governance models, and the visions of output and procedural justice in the energy transition.

Various incentives paved the way for the transfer of technology to the Middle East North Africa (MENA) region. However, they failed for a variety of reasons, among them, the issues of social and public acceptance (Komendantova *et al.*, 2017) and governance based on a top-down framework of national renewable energy master plans elaborated by the MENA governments. The realization of these plans lagged far behind the target sets, mainly because energy transition roadmaps underestimated the intricacy of managing transformative change toward sustainable energy systems (Brand, 2015).

There are several examples of good practices from Europe, such as the *Energiewende* (energy transition) in Germany or the energy transition through the climate and energy models in Austria. However, plans for the energy transition in the MENA region should consider completely different energy market structures, stakeholder networks and societal aspirations for energy, as well as climate and environmental policies in the region (FES, 2015). Careful consideration of stakeholders' views, concerns, and conflicting priorities is required for sustainable energy transition and transformation of the energy system as well as for compromise-oriented energy governance solutions.

Following the philosophical tradition of the Renaissance epoch, the human being (person, man or woman, community member, etc.) with all his or her cognition and motivation (subjective perceptions of risks and benefits as well as cognitive biases that influence decision-making, choices, and trade-offs for available alternatives) is the middle of the research. Although every policy intervention requires technological solutions, they should be based on an understanding of human reasoning, which is crucial for the implementation, adoption, and development of any technological solution.

The transition to the use of a more significant share of domestically generated resources will inevitably lead to a societal transformation that will affect the interests of existing and emerging electricity-generating industries and other stakeholders. Energy transition should focus equally on environmental protection and socioeconomic development, such as job creation and multiplier effects on local economies from investments in the RES. This chapter is based on the assumption that human factors play an important role in energy transition. As any transition has its winners and losers, it is essential to develop solutions that include various points of view—solutions that seek a compromise between

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conflicting positions or trade-offs between available alternatives. For example, conflicting views might arise from different perceptions of the risks connected with electricity-generating technologies or the costs and benefits of these technologies.

The collection of sufficient empirical data to understand behavioral factors requires the use of different methods, such as discourse analysis, multi-criteria decision analysis, games, participatory modeling, case studies, and various other methods of stakeholders' dialog. Data collection methods have included large-scale surveys, decision-making experiments, in-depth qualitative interviews, roundtable discussions, content analysis of published evidence and media reports, as well as observations of stakeholder events. The theoretical background of this work is in behavioral economics, the theory of plural rationalities, as well as cultural theory and the human beliefs model.

A new multi-stakeholder multi-criteria approach was used to collect information on social and behavioral factors. It also assessed the relevance of various electricity-generating technologies against a set of criteria under uncertainty, which reflect environmental, social, and economic components of sustainable development. Various methods are currently used to understand human factors in energy transition, including games, the human beliefs model, multi-criteria decision analysis, discourse analysis, and several others.

Discourse analysis originally appeared in linguistics as a means of analyzing factors that influence the role of language in social structures. The main aim of discourse analysis is to understand the reasoning of various groups of stakeholders, which shapes power relations and structures in society. It is used to analyze narratives that give meaning to social realities and that help people simplify complex issues to make decisions despite uncertainty. Cultural theory, which is based on discourse analysis, argues that there are several rationalities or worldviews of contested or wicked problems, such as individualistic, egalitarian, hierarchical, and others.

Based on cognitive patterns and worldviews, stakeholders have several options to select from available alternatives (when such alternatives exist). Many methods can help researchers to understand the decision-making process and to choose from among available alternatives. The games method was developed to raise awareness and teach about certain societal issues, then was expanded to better understand stakeholders' choices and reasoning. Multi-criteria decision analysis allows for the evaluation of conflicting criteria in the decision-making processes of one person or various groups of stakeholders. This method can also be used as a mediation tool to develop compromise solutions when conflicting options exist.

Several methods have been developed to understand how people make choices and which factors influence these choices. The theory of reasoned action and the theory of planned behavior claim that certain behaviors are influenced by intention, which in turn, is influenced by attitudes, subjective norms, or perceived behavioral control. Extensions of these models include moral norms, which refer to individuals' beliefs about what is right and what is wrong. The human beliefs model was originally

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developed in health science research. It includes factors that lead to changes in beliefs and perceptions and describes how these changed perceptions result in behavioral changes.

Using any of these methods requires intensive stakeholder interaction in the form of decision-making experiments, workshops, focus groups, interviews, surveys, and so on. Data from stakeholder dialogues can be analyzed with mathematical models, content analysis, regression, correlation, statistical analysis, and so on. The stakeholders who participated in this research represented various groups, including policymakers, individuals in the private sector, academics, and persons in civil society. They were identified on the basis of comprehensive stakeholder mapping and social network analysis according to their influence and role in the energy transition.

The results of projects in several countries show a high level of awareness of climate change in almost all countries. Some countries show an especially high, almost universal, awareness that climate change is happening. There is also a clear correlation between the awareness of climate change and its basis in human activity. However, this correlation varies from country to country. In some countries, climate change is clearly linked to human activity, whereas people in other countries believe that it is the result of processes in nature.

In countries such as Austria and Germany, there is an overriding acknowledgment of the need to transition to a greater share of RES. In Morocco and Jordan, the acceptance of RES is driven mainly by the energy security policy concerns, such as the need to diversify energy sources and reduce energy imports. This awareness is created by various information campaigns and efforts to communicate the need for radical change in energy generation and consumption.

Although the RES is mostly perceived as beneficial, many concerns were identified with their deployment. These concerns were mainly connected with economic factors such as the cost of energy transition, job creation, multiplier effects on local economies, or the competitiveness of local industrial enterprises as well as technical factors such as variations in generation and consumption or sufficient grid capacity. When it comes to energy-generating technologies, concerns about the safety and the cost of electricity were most frequently mentioned. This was observed not only in developing or transition economies, but also in developed economies. Our research in Morocco, Jordan, Austria, Germany, and Kyrgyzstan shows that stakeholders who are able to choose from among multiple criteria prioritize economic criteria most frequently.

The human beliefs model and the theory of behavioral control, which served as a basis for our decision-making experiments in many countries, showed that perceived ease of the use of the RES is the major factor influencing intentions to use the RES. Other factors, such as expectations of positive benefits from the use of renewable energies and moral norms, also significantly influence intention and motivate people to use the RES.

Also, various decision-making experiments showed that people tend to prioritize short-term risks (such as economic slowdowns) over long-term risks (such as climate change). Although awareness of

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the need to mitigate climate change is high, in everyday life, people prioritize actions with short-term benefits over those with long-term benefits and personal or local benefits over benefits at the global level or for future generations. The trade-offs between available alternatives and the prioritization of certain actions are some reasons why awareness of the need to mitigate climate change is not turning into action.

Another reason has to do with the feelings of ownership of energy transition. Research shows that in countries such as Austria and Germany, possibilities for the ownership of energy transition have appeared in the past few decades. These possibilities include participating in crowd financing, participating in decision-making processes through stakeholder dialogue, going from consultation to real partnership, and even seeking citizen control over the energy transition measures. There is a clear correlation between possibilities for participating in energy transition and trust in policy stakeholders who are shaping the transition.

It is also necessary to consider the variety among stakeholders' views and the need to develop compromise solutions that bring together the elements of various discourses. Discourse analysis, which we used to study stakeholder processes in Austria and Morocco, helped us to identify major arguments important to the different groups of stakeholders. These elements are classified into three large groups: individualistic, egalitarian, and hierarchical voices. The major difference among representatives of these discourses was in how energy transition should be implemented. The individualistic discourse focused on everyone's individual responsibility, the importance of progress and innovation, as well as compensation for risks and costs. The egalitarian discourse focused on joint decision-making and procedural justice as well as the equal and fair distribution of costs, the benefits and risks of energy transition, and output justice. The hierarchical discourse highlighted the value of expert-driven decision-making and government control of the risks of energy transition.

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13.4 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the study on energy policy with stakeholders in various countries, some recommendations are provided here.

13.4.1 Communicating the need for energy transition

The first recommendation has to do with communication and raising awareness of the need for energy transition. Currently, the majority of awareness-raising measures address the need for climate change mitigation, mainly from a perspective of fairness between the present and future generations as well as between various geographic regions. They also emphasize a risk perspective while highlighting probabilities and potential consequences of the risks and natural hazards of climate change. Indeed, such communication measures have been very successful. For example, in Austria, 96% of inhabitants of surveyed regions perceive the threat of climate change, 78% attribute climate change to human activity, and 61% think that mitigation measures are necessary (Komendantova *et al.*, 2018).

However, mitigating climate change requires more than raising awareness of threats and risks. As long as communication with laypeople concentrates on threats and risks not-in-my-backyard (NIMBY) behavior will dominate. The dominating discourse is that, indeed, the threat of climate change exists, and action is urgently needed, but it is mainly the task of public authorities to mitigate climate change through regulations, technology, and financing. There is also a role for private capital in financing renewable energy projects and risk de-escalation measures. In such a discourse, the role of the public is mainly discussed in frames of social acceptance or willingness to pay and use renewable energies.

Evidence from the energy generation and transmission projects in Europe shows that decision-making of the decide–announce–defend variety, in which the decision is made by the national government, aided by experts, and then implemented through a top-down approach, is no longer feasible (Wolsink, 2000; and Komendantova and Battaglini, 2016). This model often leads to conflicting opinions as well as protests that delay implementation and may even lead to the cancellation of projects (Wolfsink, 2012).

Discussions in the NIMBY framework often end up simply identifying factors for acceptance, which is a more passive attitude toward top-down decision-making that does not change anything. Nowadays, many scientists argue that NIMBY is not suited to understanding local objections and concerns. One flaw is that it does not involve local knowledge to improve the results of decision-making processes (Batel and Devine-Wright, 2015).

Climate change mitigation at a scale not only requires available technologies, regulations, and financing, but also behavioral change among millions of private households. Behavioral change is a matter of making trade-offs in decision-making, and scientific work on trade-offs—not only on energy transition but also in general—shows that people tend to prioritize economic rationality and safety. They also seek to mitigate short-term risks over long-term risks. Of course, as in every wicked policy problem, there are a variety of opinions, but this seems to be the prevalent attitude. Therefore, the recommendation is that awareness-raising measures focus on climate change mitigation as a solution that increases the quality of life now.

Behavioral change is a matter of not only communicating but also having available alternatives. People are more comfortable when they have many alternatives from which to select based on their preferred decision-making criteria, whether it be safety, energy costs, or protecting the environment. It is also not sufficient merely to have alternatives: As the human beliefs model or theory of behavioral control shows, it should also be possible to implement these alternatives. And as various decision-making experiments show, these alternatives should bring benefits in comparison to other solutions.

Therefore, the main recommendations here are:

1. Communication about the need for energy transition should go beyond such topics as communicating risks and threats of climate change or fairness among generations. It should include various discourses and narratives to address the world views of as many people as possible.

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2. Awareness raising campaigns on the need for energy transition should include information on how climate change mitigation increases the quality of life and creates co-benefits not only in the future but also in the present.
3. Communication measures should also include various alternatives and options for climate change mitigation measures.

13.4.2 Motivating the move from awareness to action

The second recommendation has to do with translating awareness of the need for climate change mitigation into action. The evidence from behavioral economics shows that active participation happens through increased feelings of ownership of the process. This ownership can manifest through the facilitation of individual actions or various collective actions such as participation in energy cooperatives. The actions can manifest through participation in decision-making processes or financial initiatives such as crowd financing. The recommendation here is that further measures are needed to strengthen the ownership of the energy transition process while going beyond the frames of NIMBY and social acceptance thinking. While developing energy policy measures on the ownership of energy transition, it might be important to consider the variety of discourses about the responsibility and ownership of energy transition and to develop compromises or solutions tailored to each discourse.

There is also a need to understand the ways that engagement and participation can go beyond the discussion of projects' details and shape the discussion of the centralized and decentralized energy transition, as this is a complex topic, where human factors play a significant role. Understanding of how participatory governance works in different countries is needed, along with how the centralization or decentralization of decision-making shapes the process of stakeholders' involvement in the discussion of energy transition issues (Komendantova *et al.*, 2015).

Although a significant part of the literature on participatory governance research is focused on Europe, evidence has also been found regarding the advantages of a participatory approach for other countries. For instance, the implications of human factors for the transformation of the energy sector in South Africa have been examined (Xavier *et al.*, 2017). Having analyzed several infrastructure projects, the authors express the need to incorporate public participation within the project cycle and institutionalize it as part of the whole decision-making process. They also find that existing conflicts in stakeholders' views and opinions can be mitigated through engagement and different methods of multi-criteria discussion.

The human factors of energy transition in various countries that influence the willingness to use RESs have been examined (Yazdanpanah *et al.*, 2015). Using the theory of planned behavior, the authors identified the main factors to be moral norms, attitudes, and perceived behavioral control, which are also connected with the ability to influence decision-making processes.

These results are also supported by the evidence available from theory and practice. The transformation of energy systems often faces risks and boundaries in terms of the implementation of climate change

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mitigation policies, which are connected with the decision-making processes (Patt, 2015). These boundaries include not only technological and economic factors but also human factors, such as the conflicting views of the risks and benefits of different technologies, as well as social and public acceptance and willingness to use technology and to pay for it (Komendantova *et al.*, 2018).

Today, public interest in the energy infrastructure is different than it was half a century ago when the existing infrastructure was built. The existing infrastructure was understood as a driver for socioeconomic development. People want to participate in the decision-making process on technologies that affect their communities. Participation in decision-making processes is often perceived as a democratic principle for the inclusiveness of people (Beierle and Cayford, 2002). The lack of opportunity to exercise this right leads to protests, implementation delays, and even the cancellation of projects due to public protests or the actions of stakeholders who were not consulted (Kunreuther *et al.*, 1994).

International legislation also declares a right to participate. The Aarhus Convention requires stakeholders to be involved in decision-making for infrastructure projects and to provide clear and transparent information about how to get involved. However, often there are limits to participation, such as the fact that the energy transition is a topic heavily dominated by technological and economic content that hinders effective public participation (Devine-Wright, 2012).

Different views exist on participatory governance. Some argue that a complex decision-making process regarding critical infrastructure, such as energy, should be left in the hands of experts and scientists. Public participation would thus be reserved for evaluating this decision-making process and its outcomes (Rowe and Frewer, 2000). Others argue that participation is beneficial because it brings out the knowledge of stakeholders at the national level (Hänlein, 2015), which might otherwise be limited, such as the knowledge of local areas (Jasanoff, 1998). There is also evidence that integrating the views of all stakeholders—not only those of specialized experts—can enhance the legitimacy of decision-making and build trust (Renn, 2008).

Therefore, the main recommendations here are:

1. Feeling of the ownership of energy transition should be stimulated. There should be various alternatives for creating ownership from participation in financing to participation in decision making processes.
2. Further understanding of the potential and implementation of participatory governance of energy transition is needed.

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CHAPTER

14 RENEWABLE ENERGY IN DEVELOPING COUNTRIES

Yarub Al-Douri

Al-Douri, Y., "Renewable energy in developing countries," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 14-1–14-18.

14.1 INTRODUCTION

The government of Iraq is not aware of the significance of renewable energy (RE) due to the abundance and extra quantity of fossil fuel that would be needed in the Middle East; the need for energy in Iraq began due to the destruction and disruption that happened in 1991. The requirements for solar energy should be taken into account immediately due to global climate changes causing international warming (Jacobson *et al.*, 2013). Solar energy reaching the globe is estimated to be 233 PW in comparison with the consumed 24 TW power yearly (Hernandez *et al.*, 2014). The deserts of the globe receive more solar energy than people's annual consumption (Lau *et al.*, 2012). The Iraqi desert in the west of Baghdad has the biggest solar energy-based electricity generator that generates 1776 MJ/m^2 power. It generates 3140–3373 MJ/m^2 mean power density, while the German Aerospace Centre (DLR) refers to the 26 860 MJ h/m^2/year peak power density (Sørensen, 2004). There is a real opportunity for Iraq to be a dominant supplier of renewable energy and solar energy exclusively in the Middle East and international market.

The emission of carbon dioxide via fossil fuels and biofuel can be solved by implementing solar energy. Solar energy is an important factor of analysis, characterization, and application due to increased global warming (Jacobson *et al.*, 2013) and its effect on the global climate (Hernandez *et al.*, 2014). It is known that only 24 TW power are consumed out of the 233 PW of sunlight incidence on the globe. Furthermore, energy from sunlight received by the globe's deserts within 2 h is more than enough for humankind's requirements for one year (Feltrin, 2008). Due to the availability of huge deserts in Saudi Arabia (KSA), solar energy-based electricity generation is possible for the Middle East. The global solar energy-based electricity generation is 0.003 GW/year. So, the KSA has the bigger chance for harnessing solar energy to generate electricity in the future instead of fossil fuels (Taleb, 2009).

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For North Africa, natural gas and oil constitute hydrocarbons necessary to generate energy that is essential and important in Algeria, which constitutes 93.6% of Algeria's exportation, and roughly 90% of Algeria's electricity is produced from the hydrocarbons of natural gas and oil (Khraief *et al.*, 2018). The diversification of the national economy and the creation of new socio-economic dynamics around renewable energies are becoming essential goals of the Algerian government. This is mainly due to the fact that Algeria possesses a huge potential of renewable energy resources such as solar, wind, hydro, biomass, and geothermal energy (Haddad *et al.*, 2017) to utilize, consume, and employ them for addressing the increased demand of energy, as well as to save sources of energy to support the national exportation in the future.

Furthermore, the dilemma of energy in Morocco represents 96% of total importations of the country's requirements. In addition, there was an increased observation of energy consumption estimated by an annual rate of 5.7% for the period 2002–2011 (Supersberger and Fuhrer, 2011). The fluctuation in oil's price and energy dependent importation has made Morocco a vulnerable and highly affected country due to the increasing oil's price in the international market, which shocked the gross domestic product (GDP) due to 61% of Morocco's energy consumption depending on petroleum (Ministère de l'Energie, des Mines, 2012). Morocco's electricity demand rose on average by about 5% per year in the past five years and is expected to increase by 7%–8.5% per year in the next ten years. In 2011, electricity consumption was 28.8 TW h, which is 8.4% more than the previous year [Office National de l'Electricité (ONE), 2010]. About 81% of the country's electricity production is based on fossil fuel like coal, oil, and natural gas (German Development Institute). Coal power plants, fueled by importing hard coal, form the backbone of the country's electricity generation system. With an installed capacity of 1.8 GW (Morocco's total capacity is 6.4 GW), they contribute to about 45% of the country's forecast electricity production of 26.5 TW h. About 12% of Morocco's electricity demand is currently supplied by open cycle and combined cycle gas power generation, and this share is expected to rise with additional combined cycle power plants in the near future (Brand *et al.*, 2012).

For Asian territories, the following are aimed for study: the first is related to the global crisis of CO_2 emission; that is, the long-run and short-run impacts will be examined for the global crisis of CO_2 emission. The second aim is to focus on the growth of economy by demanding energy for determining the energy consumption per Pakistan's economy request. Third is to employ the technology innovation (TI) for reducing CO_2 emission in Pakistan. Fourth is to characterize the global effects of asymmetry to investigate the role of TO in reducing the emission of carbon dioxide in the long- and short-term that has implications on Pakistan's economy development (National KeTTHA, 2008; Mekhilef *et al.*, 2014; Kardooni *et al.*, 2016; and Oh *et al.*, 2018).

On the other hand, Malaysia has made noticeable attempts related to the development of renewable energy for diversifying the sources of energy-based electricity generation by following up with the international market of energy (Fairuz *et al.*, 2013; Petinrin and Shaaban, 2015; and Hussien *et al.*, 2016). It was found nationwide that the consumed efforts had unsuccessful outcomes in addition to the government's observation that the approach of business-*as*-usual is unproductive and unfit

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in developing sustainability. It is very necessary to consider the lessons of the mentioned approach; therefore, there were real and huge works done by the Malaysian government to establish and formulate the National Renewable Energy Policy and Action Plan in 2008 to build a holistic and new approach for the study and application of renewable energy in Malaysia. It was aimed to increase the deployment of renewable energy for supplying electricity all over the nation and supporting socio-economic development and sustainability. Here, the importance and necessity of the research and development (R&D) principle for any project or idea is highlighted with a focus on the acceleration, growth, and industry of renewable energies. Therefore, innovation and invention in service and products pave the way for ensuring and gaining green and sustainable economy (Fairuz *et al.*, 2013).

14.2 STATUS OF IRAQ FOR RENEWABLE ENERGY

It is estimated that there are 3000 solar radiance hours yearly received by Baghdad (Abed *et al.*, 2014). The variation in the intensity of solar energy is observed clearly in January (4836 MJ/m^2) and June (9686 MJ/m^2). There are many theoretical and experimental research studies that are focused on Iraq (Al-Riahi *et al.*, 1992; Al-Riahi and Al-Kayssi, 1998; Dihrab and Sopian, 2010; and Kazem and Chaichan, 2012) that present a homogenous balance between experimental and theoretical results (Bataineh and Al-Odat, 2010). Moreover, these research studies are focused to develop and improve solar energy technologies for electricity generation (Ahmed *et al.*, 1983; and Abass and Chaichan, 2009). It is important to mention that the presence of solar radiation data is necessary for economic purpose for recording solar energy (United States Department of Agriculture, 2009; and Ahmed, 2010). To summarize, the radiation of solar energy features in Iraq are the following:

1. In the north, the intra-annual variation is ∼300%, from December–January (7 MJ/m^2) to June–July (23 MJ/m^2), while in the south, the intra-annual variation is ∼200%, from December–January (13 MJ/m^2) to June–July (27 MJ/m^2). In the center, the intra-annual variation is ∼250%.
2. The correlation between geographical sites (north–south) with solar energy is inverse; it is increased and decreased in winter and summer, respectively.
3. The solar energy variation in Iraqi geographical sites (east–west) is almost small but is subject to estimation errors.
4. To evaluate the solar energy radiation, it depends on the relations extracted from the data measured at meteorology stations at big towns and cities (Sissakian *et al.*, 2012).
5. PV technology is appropriate for producing electricity and off-grid electricity generation.

To share and expand renewable energy sources for replacing available fossil fuels, future predictions are not considered. Those considerations include different types of renewable energy plans; wind, solar, biomass, and hydro to generate electricity to reduce dependent fossil fuels. It is well-known that the amount of radiation from solar energy on the globe is varied based on the surface location of the Earth, subjected to many properties attenuating different surface areas, geographic sites, and the atmosphere (Sayigh, 1987). The north of Iraq consists of mountains, where the sunlight time and age are different

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Table 14.1
Estimated solar radiation and sunshine for the period (1995–2012) (Abed *et al.*, 2014).

	Haditha		Beji		Samara	
Month	***Sunshine***	**MJ/m² day**	***Sunshine***	**MJ/m² day**	***Sunshine***	**MJ/m² day**
JAN	5.875	11.91	5.765	9.64	5.876	8.41
FEB	7.229	15.64	6.529	12.84	6.9	10.78
MAR	7.954	20.89	6.988	16.75	7.614	14.67
APR	8.379	26.25	7.871	21.38	8.71	16.21
MAY	9.992	30.3	9.041	24.05	9.962	19.81
JUNE	11.95	31.83	11.382	27.01	11.033	21.45
JULY	11.942	31.86	11.265	26.72	10.652	21.9
AUG	11.408	29.44	11.029	24.89	10.224	20.57
SEP	10.267	25.43	10.047	21.31	8.929	17.69
OCT	8.558	19.37	8.135	15.94	7.867	12.78
NOV	7	14.46	6.294	11.65	6.452	9.31
DEC	5.792	10.63	5.318	8.96	5.29	7.5

than other parts of Iraq with a focus on the winter season. The geographic nature of the middle of Iraq is plain including two important rivers, the Euphrates and the Tigris, where the sunlight time and age are higher than the north of Iraq. The atmosphere is very pure in the south of Iraq except for the storms of dust that come from the neighbor desert, but the region favors the greatest global solar energy radiation. The average radiation yearly in the south of Iraq is calculated to be 7263.97 MJ m² larger than the same one in the north of Iraq calculated to be 6318.83 MJ.m² (Abed *et al.*, 2014). The office of Iraqi meteorology archives could provide monthly relative humidity, mean radiation of daily solar energy, maximum temperature, and sunshine duration (Al-Salihi *et al.*, 2010). The estimated radiation of global solar energy and sunshine in the west and north of Iraq (Haditha, Beji, and Samara) over 17 years is displayed in Table 14.1 (El Bassam *et al.*, 2013).

18.57 MJ/m² is the average solar radiation yearly in Baghdad, followed by 14.75 MJ/m² in Mosul and 18.53 MJ/m² in Rutba, with reference to the direct measurements in the month of July for the high temperature and months of December and January for the low temperature (Majeed, 2013; and Al-Douri and Abed, 2016).

14.2.1 Future of renewable energy in Iraq

The presence of solar radiation data is necessary for commercial purposes. So, it is necessary to measure and keep the mentioned data for evaluating the advantages of solar energy (Abed *et al.*, 2014). The following points summarize the features with regard to solar energy radiation in Iraq:

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1. In the north, south, and center of Iraq, there are real technological attempts to increase the intra-annual variation for the periods of December–January and June–July to be more than the expected rates to consume more renewable energies.
2. The intended technological attempts are planned to employ them to save good radiation rates in the north of Iraq, especially in the winter season to save more energy and support national economy. The uniform distribution of radiation along whole Iraq is observed during summer from June to August.
3. The mentioned technologies will save the continuity of solar energy without variation from east to west Iraq and avoid any estimated errors.
4. The mentioned technologies will evaluate the radiation of solar energy exactly depending on the relations exploited from data measured at meteorology stations at different towns and cities (Sissakian *et al.*, 2012), in addition to correcting the errors in the circumference because of pollution; therefore, it is fine to say that the actual radiations are bigger than measured values (Majeed, 2013).
5. PV-based nanotechnologies are very appropriate for producing highly efficient electricity for a uniform distribution of solar radiation for all of Iraq.

Efficient PVs are affected by of dust contamination and increased temperature. Because the weather in Iraq is dusty, it is important to research the dust rate, type, accumulated density, and external effects on the PVs' performance. The availability of gas and oil in Iraq in a huge amount is an impetus to announce scientifically that the real extent of gas and oil are not definitively known, especially in the south of Iraq from Bahr al Najaf desert to the extreme border of the south of the country (Al-Douri and Abed, 2016). In Iraq, there is an attention to expand and invest in the consumption of fossil fuels in the energy sector and related activities. However, the current situation of Iraq is bad and its future is dark; therefore, the awareness of future transportations, such as electric cars, and future plans of mass transportations and infrastructure are absent totally. Unfortunately, the thinking and eagerness to share, expand, and consider renewable energies instead of the consumption of fossil fuels are not attended completely, although the world is going to firmly establish nanotechnology-based renewable energies and reduce fossil fuels for generating electricity that is planned to consider the solar energy abundance as explained upon. The sources of renewable energy include CSP plants, PVs, biomass, wind, and hydro.

14.3 THE OUTLOOK OF RENEWABLE ENERGY IN KSA

Human health faces serious threats due to air pollution. The gases emitted from traditional industries for generating fossil fuel-based electricity cause harmful diseases (Al-Douri *et al.*, 2019b). The emitted gases that pollute the environment affect the health of the people in KSA is attributing to the lowest quality of fuels like sulfur mixed with crude oil in addition to the absence of emission control (U.S. Department of Energy). The principal contributors to global warming are greenhouse gases and CO_2 emission like

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SO_2 and NO_x emitted by traditional power plants. The KSA is regarded the first country in the Gulf Cooperation Council (GCC) with a percentage of 56% from the CO_2 emission viewpoint (Qader, 2009), and on a global scale, KSA is ranked 14 (Al-Douri *et al.*, 2019b). Figure 14.1 shows an increase in the consumption of electricity. Therefore, the emission of CO_2 is increasing dramatically along with the use of traditional techniques for generating electricity to the available capacities. To curb the emission of CO_2, nanotechnology-based electricity generation uses arrays of PVs using quantum dots (QDs).

The Meteorology and Environment Presidency in the KSA in managing the standard of environmental protection states that the particulate matter (PM) within average concentrations should be within 80 lg/m^3/year. Unfortunately, the concentration of PM in KSA is about 113 lg/m^3 (Presidency of Meteorology and Environment in Saudi Arabia, 2001). Following the statistics of the KSA in 2008, the amount of SR0.15 is the governmental average cost for one unit of traditional electricity (Kroposki *et al.*, 2009), while the typical cost in GCC countries is 12 ¢/kWh (Booz & Company, 2009), which is equal to SR0.45. One ton of petroleum produces 6.28 barrels to generate 11 630 kWh of traditional electricity (Al-Douri *et al.*, 2019a). Due to the dramatically increased prices of oil, a barrel's price has hit the ceiling of $95 in 2015 to $108 in 2020 (Plaz, 1978; and U.S. Energy Information Administration, 2010). All these circumstances will affect traditional electricity prices and make the decision to invest in renewable energies inevitable to compete in real with traditional electricity for lesser prices. In addition, tone should take into consideration all the unexpected costs of traditional electricity focusing on the impacts of health and environment (U.S. Department of Energy). From a geographical viewpoint, the economy and radiation of solar energy are good. The comparison between traditional and solar energies, the unexpected costs of fossil fuel, and its effect on the environment and health should be taken into consideration.

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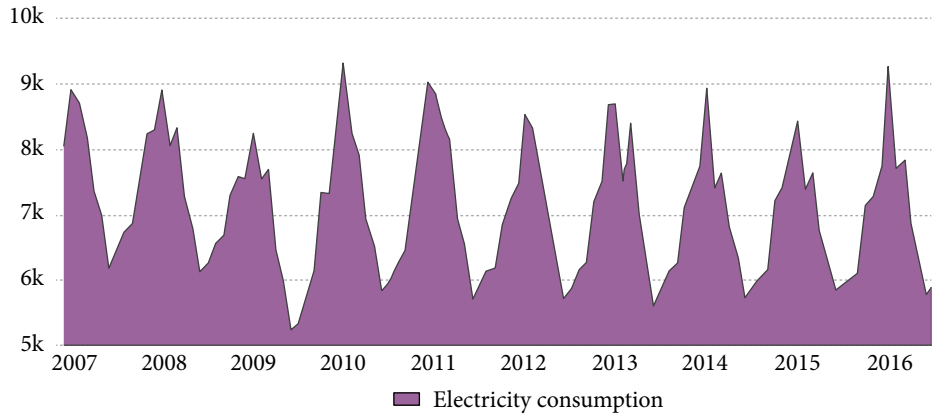

FIG. 14.1
Electricity consumption in KSA (Al-Douri *et al.*, 2019b).

14.4 RENEWABLE ENERGY DEVELOPMENT IN ALGERIA

Distinguished efforts to develop a section of renewable energy in Algeria have been taken to create a new institution named the Ministry of Environment and Renewable Energies (Bouraiou *et al.*, 2020). Furthermore, a renewable energy and efficiency development program has been adopted by the Algerian government in 2011 and revised in 2015 (Ministry of Environment and Renewable Energies).

The main directions of this program are cited below (Saiah and Stambouli, 2017):

- Program to develop renewable energy
- Program to develop saved energy and efficiency
- Regulatory and legal framework
- Program to develop capacities of industries
- Research development.

There are pillars to address the following:

a. Program to develop renewable energy: Plans to implement renewable energy-based electricity production utilizing cogeneration, biomass, wind, PVs, solar thermal, and geothermal energies are considered in Algeria. Those sectors of the mentioned renewable energies will be a real engine to sustain the growth of the economy and its development. Renewable energy in Algeria will generate 37% of Algeria's capacity by 2030 and 27% of Algerian consumption of electricity generation. Solar energy is a dominant type of renewable energies in Algeria. To develop the economy, create job opportunities, and establish industries for the best future, solar energy can be considered and supported firmly (Ministry of Energy). The program of renewable energies is presented in Table 14.2 to realize the Algerian market for the period of 2015–2030 (Bey *et al.*, 2016; and Mokhtara *et al.*, 2021).

Table 14.2
National renewable energy development program over 2015–2030 (Bouraiou *et al.*, 2020).

Unit: MW	1st phase (2015–2020)	2nd phase (2021–2030)	Total
Photovoltaic	3000	10 575	13 575
Wind	1010	4000	5010
CSP	…	2000	2000
Cogeneration	150	250	400
Biomass	360	640	1000
Geothermal	5	10	15
Total	4525	17 475	22 000

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b. Energy efficiency and energy saving development program: The key actions of energy efficiency and energy saving development program are presented (Ministry of Energy) below:
   - Insulated thermal buildings
   - Promote solar water heaters
   - Disseminate the utilization of saved energy
   - Incorporate the energy performance in public life
   - Promote efficient energy in the industry sector
   - Promote GN/C and GNL/C.

14.5 RENEWABLE ENERGY POTENTIALS IN MOROCCO

Morocco is in the extremely west part of the Arab nations; it is a fossil fuel-dependent country. Morocco is importing 96% of its necessity of energy. Meanwhile, it has plenty of renewable energy sources such as solar and wind (Kousksou *et al.*, 2015). Therefore, the Moroccan authorities have focused on developing renewable energies for creating job opportunities, maintaining sustainability, achieving energy security, and investing in renewable energies.

14.5.1 Wind energy

Morocco has a bright future for investing in wind energy to be a promising source of renewable energy because of its performance for meeting the increasing demand of electricity (Shafiullah *et al.*, 2013). 17 400 MW is the total wind energy capacity by 2000; on the other hand, the capacity increased to 237 669 MW by 2011 (Kumar and Kandpal, 2007). To expand the capacity of wind energy, it is compromised to play an important role to mitigate the climate change (Ozgener *et al.*, 2004). Wind energy-based electricity is a pollution-free, competitive, and mature technology widely spread in many parts of the world (Balat, 2009). Wind power is converted to electricity utilizing specific turbines. The mentioned power varies from 750 kW to 2.5 MW (Randolph, 2008). The other important parameter is the wind turbine height, which affects its appropriate of the geographic site to be roughly 450 m (Benkhadra, 2011), requiring higher turbines to be built.

14.5.2 Hydroenergy

Flowing water can create potential and kinetic energy that can be converted to mechanical power by turbines and driving generators. Hydroenergy is a type of renewable energy that is an advanced technology to generate electricity. So, hydroelectricity represents 17% of electricity consumed worldwide (Moriarty and Honnery, 2012). The potential of hydroelectricity in Morocco is incited via four rivers and several dams. So, the generation of hydroelectricity is estimated to be about 5000 GW h/year (Agence National pour le Développement des Energies Renouvelables et de l'Efficacité Energétique,

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2011). 1360 GW/h was produced in 2008 via hydrodependent power via the moderator ONEE for operating 26 stations of hydroelectricity. Additionally, 464 MW comes from the hydro-electricity station pumped in Afourer close to Beni Mellal.

14.5.3 Solar energy

The demand for solar energy in Morocco increased dramatically one decade ago due to the mature PV technologies and their costs are reasonable (Mills, 2004). There are two famous types of PV technologies nowadays: (i) first generation of Si-based PVs and (ii) second generation of thin film-technologies synthesized by different ranges of semiconductors including copper indium gallium and amorphous Si cadmium–telluride. Those types represent the following: decentralized, off-grid and centralized, or grid connected systems. 200 kW power is a stronger growth at centralized PVs to operate as plants of centralized power. It was recently announced in Morocco for developing units of combined cycle with projects of Integrated Solar Energy Generation (Integrated Solar Energy Generation Project).

14.5.4 Biomass energy

It represents 10% of the global energy worldwide and ranks fourth after other known sources of oil, coal, and gas. Biomass-dependent energy production is estimated to be 53 EJ. 86% of biomass is consumed for producing cooling/heating industrial potential applications. In Morocco, there is a golden opportunity for biomass-dependent energy due to availability of a huge amount of animal, agricultural, and continuous waste (Afilal *et al.*, 2013).

14.5.5 Geothermal energy

It is well-known in Morocco; the direct utilization of geothermal energy is limited to swimming pools, balneology, and potable waters. There is a notable progress to reconstruct swimming pools in the last decade followed by the increase of newly built outdoor pools of; it is for a specific market of Morocco (Zarhloule *et al.*, 2010; and Boulakhbar *et al.*, 2020).

14.6 THE ROLE OF RENEWABLE ENERGY IN REDUCING ENVIRONMENTAL DEGRADATION IN PAKISTAN

This is a first-ever study for Pakistan focusing on the role of renewable energy to reduce the emission of CO_2 (Chien *et al.*, 2021). The Quantile Autoregressive Distributed Lag (QARDL) approach is opted for analysis (Choi *et al.*, 2010) to discover the asymmetries in the long- and short-run for the different interest variables in Pakistan. QARDL presents a further advantage for testing the stabilization of

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long-run relations across many quantiles, providing a wide range of realizations to link between RE and its effect on the emission of CO_2. In Pakistan, the assessment of QARDL for the long-term association between CO_2 emission and RE is considered; also, it estimates the dynamics of short-term across different quantiles of CO_2 emission. Nonetheless, QARDL is a suitable technique to characterize the quantile presence with regard to the cointegration of short-run coefficients, and long-run ones attributed to monotonic variables. In Pakistan, there are vital and continuous debates for reducing CO_2 emissions through understanding of RE to protect Pakistan's economy in the future by establishing technology-based green development and growth, which contribute to sustainable and developed economy (Chien *et al.*, 2021).

An alternative is being examined to reduce the emission of carbon dioxide, but conflict risk reduction and tackling terrorism by adopting the energy security principle based on the transition to renewable energies remain largely ignored in the international debate. However, eliminating the risks of conflict and tackling terrorism using renewable energy will require modifying the available policies and regulatory frameworks for the accelerated energy transition (Luqman *et al.*, 2019; and Mohamed *et al.*, 2019). As a whole, these studies have succeeded in refuting the hypothesis that generally there is no relationship between RE and reducing environmental degradation, thus demonstrating that there is no disproportionate long-term effects on the economic growth of Pakistan (Mohamed *et al.*, 2021).

14.7 RENEWABLE ENERGY PROGRESS IN MALAYSIA

Malaysia is blessed with abundant potential renewable energy resources like solar, wind, hydro, biomass, and biogas (Azman *et al.*, 2011; Gomesh *et al.*, 2013; Ahmad and Tahar, 2014; and Mohd Chachuli *et al.*, 2021). Malaysia has put forth tremendous efforts toward renewable energy deployment, particularly for electricity generation (Petinrin and Shaaban, 2015). The Malaysia Building Integrated Photovoltaic (2005–2011), Biomass-based Power Generation & Co-generation in the Malaysian Palm Oil Industry (2002–2010), and Small Renewable Energy Power Program (2001–2010) projects have shown interest to implement their policies (Azman *et al.*, 2011; and Gomesh *et al.*, 2013). Those are aimed to develop renewable energy sources for utilizing the power (Gomesh *et al.*, 2013). The initial target to generate renewable energy-based electricity is 500MW, but only 12 MW was generated by 2005 (Economic Planning Unit, 2001). However, 58.1 MW of renewable energy generation was generated by the end of 2009 (Khor and Lalchand, 2014). The National Green Technology Policy was established in 2009 by the government of Malaysia to show its interest and seriousness to consume renewable energy-based electricity generation for various green applications to achieve and reach efficient renewable energy-based electricity generation (KeTTHA, 2009). The Tenth Malaysia Plan (2011–2015) was established to focus on the importance of renewable energy-based electricity generation in Malaysia (Economic Planning Unit,

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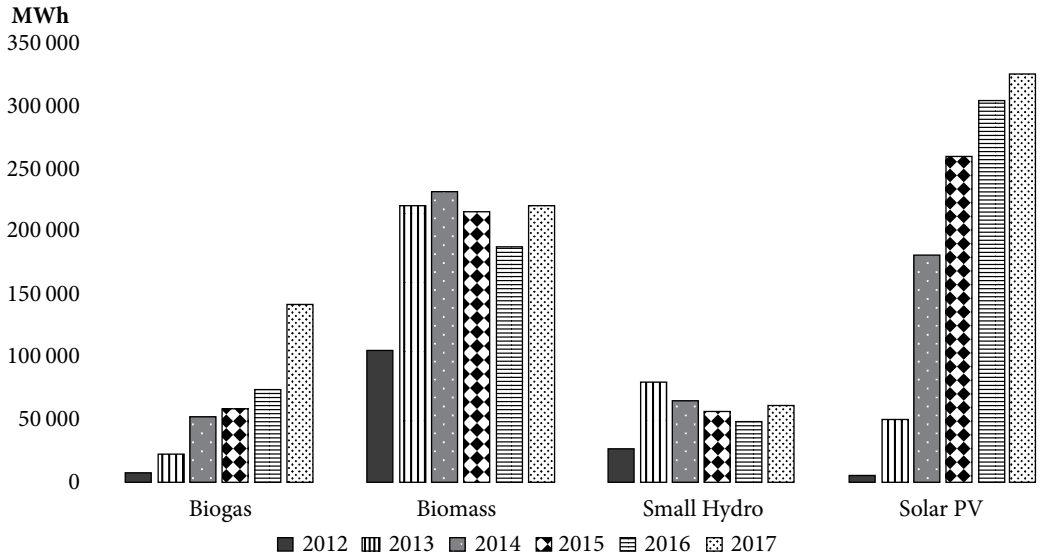

FIG. 14.2
Renewable energy-based power generation in Malaysia (Mohd Chachuli *et al.*, 2021).

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2011). Officially, the Feed-In Tariff (FiT) including renewable energy was enacted in 2011 to present the importance of renewable energy-based electricity generation in Malaysia (The Government of Malaysia, 2011). The four renewable energy resources that are eligible for FiT are biogas, biomass, hydro, and photovoltaics. So, to mitigate the phenomenon of greenhouse emission (GHG), it is inevitable for the government of Malaysia to rely on the importance of renewable energy via increasing the contribution of mixing of energies nationwide. Given the tremendous effort made by the government, the electricity generation from renewable energy achieved its contribution in the energy generation mix in 2015 by 1% (Fig. 14.2) [Suruhanjaya Tenaga (Malaysian Energy Commission), 2017]. Huge support of the government of Malaysia to the sector of renewable energy is considered and expected to contribute the mixed energies for accommodating future issues with regard to the environment (Fig. 14.3). For measuring efficient performance of output and input variables, it is advised to use a method (non-parametric) called Data Envelopment Analysis (DEA). For studying renewable energy applicable to DEA, there are three principal topics: (1) Efficient renewable energy measurement for deployment at the state or country level (Khoshnevis and Teirlinck, 2018; and Li *et al.*, 2018), (2) measuring the efficient renewable energies technology (San Cristobal, 2011; Yan *et al.*, 2017; and Niu *et al.*, 2018), and (3) assessing effective policies of renewable energies (Chien and Hu, 2007; and Woo *et al.*, 2015).

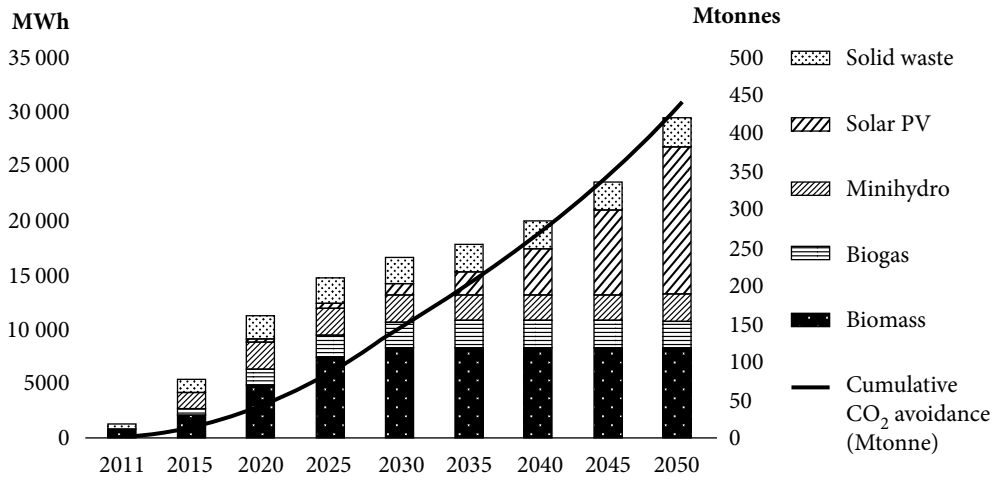

FIG. 14.3
Malaysia's plan to avoid CO_2 and targeting renewable energies (Mohd Chachuli *et al.*, 2021).

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14.8 CONCLUSIONS

It has become a necessity for vast investment to develop the solar energy infrastructure in Iraq in terms of localized plants with viable storage capacity to serve the growing energy demands. Therefore, the renewable energy may have great potential if environment friendliness has to be considered. Renewable solar energy is to fulfill the electrical power requirements of Iraq as a solution to reduce CO_2 emission. Solar energy is the cheapest recommended and available source for converting, utilizing, and investing in different electrical projects and plans within the KSA, as it is verified that solar energy-based electricity can generate 0.003 GW. In addition, it is demonstrated that other renewable energy types such as PVs and wind turbines are suitable and regarded reasonable. 50% of energy produced in the KSA comes from power plants of gas turbines for reducing CO_2 emissions. Renewable energy potential in Algeria has exhibited to reach 354.4 MW until 2018. However, the current installed capacity for renewable energy production remains weak compared to the huge potential that characterizes the Algerian territory. Due to abundant solar energy in Algeria, PVs had crowned the chair of renewable energies. To promote the development of renewable energies in Algeria, the following are needed: (1) Improvement of conditions for implementing of Algerian renewable energy programs, (2) support the implementation of favorable regulatory for sustainable energies policy, (3) to contribute a long-term investment in renewable energies, and (4) to establish different renewable energies institutions. Morocco had achieved significant progress development of renewable energy (RE). It had characterized

the possible barriers that could retard the growth of RE as the following: (1) To define financial schemes for helping renewable energies producers by fiscal and/or economic incentives; (2) special tax, incentives, and higher tariff reliefs for promoting the renewable energies sector; (3) to define and guarantee the development, internal mechanism, and market requirements of renewable energies; (4) required information on using renewable energy and its impact on the environment should be supplied to the public; and (5) to promote research, development, and education programs for the best future of renewable energies technology. The case study of Pakistan is vital to describe the cause-and-effect patterns through different quantiles of the variables of interest as RE. It had provided interesting insights for the policy practitioners. For RE in Pakistan, it is negatively and significantly associated with CO_2 emissions. It is displayed that at early steps of growth, the commercial activities trigger different types of emissions. There are important strategies for decreasing CO_2: (1) accelerating the transition to carbon-free energy and (2) focusing on applying industry-leading green concepts. A DEA method was presented to evaluate the R&D efficiency activities of solar, wind, biomass, biogas, and hydroenergy by assuming the FiT program in Malaysia. In Malaysia, a systematic R&D program and economic gain illustrate that the hydro type of renewable energies is an efficient type of renewable energy in terms of R&D activities for utilizing and producing optimum electricity (Naderipour *et al.*, 2020).

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CHAPTER

15 RENEWABLE ENERGY IN RURAL AREAS

Hussein A. Kazem and Miqdam T. Chaichan

Kazem, H. A. and Chaichan, M. T., "Renewable energy in rural areas," in *Renewable Energy: Analysis, Resources, Applications, Management, and Policy*, edited by Y. Al-Douri (AIP Publishing, Melville, New York, 2022), pp. 15-1–15-20.

15.1 INTRODUCTION

Today, civilization depends on the production of electrical energy for industrial, residential, and commercial purposes. A greater part of this electricity is produced using fossil fuels at a rate of more than 85% of the global electricity demand. The combustion of fossil fuels causes the emission of greenhouse gases with devastating consequences in humans, animals, plants, and the environment (Marefati *et al.*, 2019). These gases cause the dangerous phenomenon of global warming, which is the increase in the temperature of the atmosphere that causes an increase in the temperature of the earth's surface. One of the most dangerous of these gases is carbon dioxide emitted from the complete combustion of fossil fuels in all forms. At the same time, what makes the situation more complicated is the steady increase in the world's population as the demand for electricity increases annually. Ağbulut *et al.* (2021) showed that the demand for electric power has increased by 1.7% annually in the past ten years.

40% of global electricity consumption is used by buildings, and this percentage represents an equivalent of 30% of the total carbon dioxide emissions around the world. The increased need for electricity in buildings is due to the extensive use of new and advanced electrical equipment, in addition to the widespread use of smart devices.

The use of electricity at a certain level varies according to the socioeconomic status and standard of living of the person, which is an indicator for determining the living condition of the family. Electricity provides an improved quality of life for families, which contributes to the development of the entire nation. Nations are currently improving the quality of life and achieving social and economic growth, all of which are linked to the average per capita consumption of electricity. People's access to electricity is a key factor in improving their quality of life. Most buildings in the world are concentrated in urban

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communities and are connected to a grid. However, many small and rural communities cannot access the electric grid due to their location far from urban communities (cities and towns). Such societies are found in separate areas of the desert or on islands far from the coast (Duic and Carvalho, 2004). Connecting these communities to the national grid is very costly and has technical difficulties. Therefore, most of such societies depend on diesel generators as their main source of electricity (Poggi *et al.*, 2018).

There are approximately 1.2×10^9 people around the world who do not have access to electricity. Statistics also show that more than 300×10^6 people in India and the same in China, and about 50×10^6 people in Africa do not have access to electricity connected to the grid. More than 3×10^6 inhibitors all around the world still depend on wood, charcoal, and dung for cooking and heating (Chaichan and Kazem, 2018).

There are more than 100 000 islands on the planet, with a total area equivalent to 1/6 of the land area. These islands are spread in all latitudes and longitudes, and their population exceeds 500×10^6 inhabitants. Islands are difficult to supply with resources and are not always energy self-sufficient (Al-Maamary *et al.*, 2017).

In general, the basic need that can be considered globally is reliance on renewable energies, which is based on environmentally reliable and naturally available systems (Kåberger, 2018). According to global statistics, since 2010, global non-hydropower renewable energy production has reached 3.3%. This dependence on renewable energies is constantly growing with the support of new policies that succeeded in raising its rate to 5% in 2011 (McLoughlin *et al.*, 2012). Renewable energy systems provide

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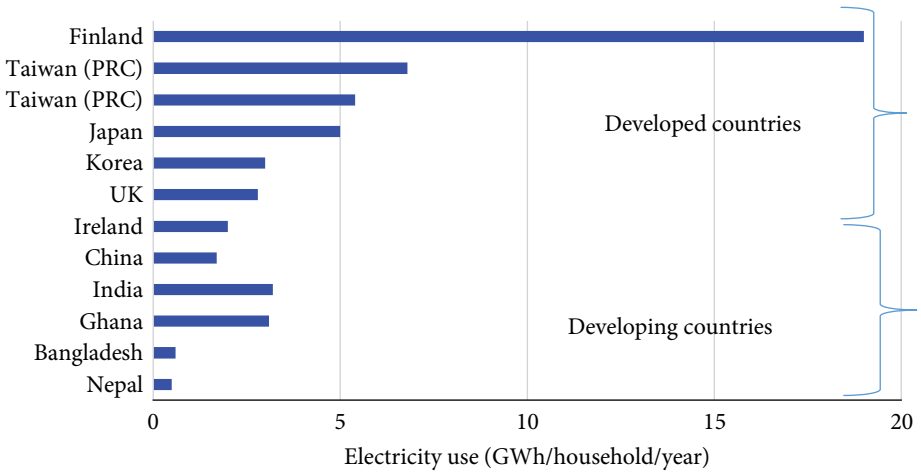

FIG. 15.1
Electricity use in developed and developing countries.

feasible electrification in poor, off-grid rural areas. One or more types of renewable energy systems can be used as wind energy, solar energy, hydropower, etc. Recently, many researchers have encouraged the use of hybrid renewable energy systems (HRESs) that include two or more different renewable energy systems in addition to different energy storage systems (ESSs). These systems, as indicated by their fans, give a promising potential for the electrification of remote areas.

Figure 15.1 shows the average annual electricity consumption in developing and developed countries per household. Households in developed countries consume electricity at a very high rate compared to households in developing countries. The figure shows that only in India and Ghana do families consume electricity rates comparable to the developed countries. As for the rest of the developing countries, except for Ghana and India, their electricity consumption is low. Household electricity consumption in these two countries is equivalent to more than six times that of a household in Nepal (Owusu and Asumadu-Sarkodie, 2016).

15.2 ENERGY SITUATION IN RURAL AREAS

Developing countries face two main problems in the energy sector. First, they are almost completely dependent on fossil fuels for energy, which has negative impacts on the economy, the environment, and health. Second, resources such as oil products and liquefied natural gas used in the production of electricity cannot be accessed equitably between developing countries or within these countries and between different urban and rural societies. Therefore, we find discrepancies in societal equality, quality of life, and economic and social level. In developed countries with high consumption of electrical energy, they are still using fossil fuels to meet their energy needs. These countries are currently working on adopting new plans to balance electricity consumption, while preserving the advanced quality of life that their citizens live. Most of the developing countries need to double their electricity capacity to reach better development. At the same time, they need to reduce their dependence on fossil sources for electricity production (Ramli *et al.*, 2016).

Today, electricity produced from renewable sources can be considered cheaper than oil, and the shift toward renewable electricity will provide employment opportunities for the workforce—in addition to providing an effective means of transport with high efficiency in saving energy, and its environmental impacts are low. The tendency of developed countries to reduce high energy consumption to average does not necessarily mean an impact on the standard of living and quality of life for people in these areas.

Figure 15.2 shows the curves of the average annual rate of per capita electricity use in some south Asian countries that are considered developing countries for the period from 2000 to 2014. The curves show that Indian citizens consumed the highest rate of electricity during the above period, while Nepal citizens consumed the lowest rate of electricity among the Asian countries as in the figure. Sri Lanka, Pakistan, and Bangladesh citizens consumed electricity at a higher rate than Nepal. The figure also

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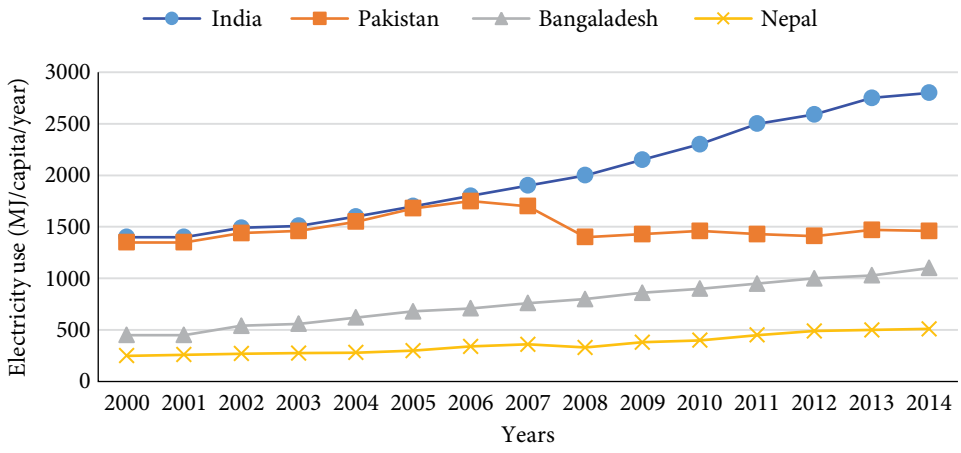

FIG. 15.2
Electricity use trend in South-Asian countries from 2000 to 2014.

shows a clear development in the per capita consumption rate of electricity in India and Bangladesh during the listed years, compared to the rest of the countries.

It can be said that the rate of advancement of industry and the economy is slow in developing countries owing to their political and economic conditions, and this justifies the fact that the rate of electricity use is the lowest in the world. Also, these rates may not be acceptable from the point of view of citizens in developed countries. Therefore, the infrastructure of developing countries must first be developed to improve their energy situation. In such countries, this improvement completely depends on the policies of their governments and the extent of their interest in developing the renewable energy sector in remote communities (Poggi *et al.*, 2018).

Also, the level of household income can be adopted as an indicator of the standard of living, as the household income in cities is usually much higher than the average income of families in remote areas. The income level is reflected in the electricity consumption as previously mentioned. For example, Nepal, as we mentioned earlier, is considered one of the countries in the world that consumes less electricity and is dependent mostly on firewood for power generation. In the urban areas of Nepal, the average household income is higher than in semi-urban or remote areas, which is reflected in their increased electricity consumption. In remote areas, the average household income is low, as is the rate of electricity consumption.

Remote areas are characterized by their low level of education, as most of their residents do not go beyond primary school. There are relatively fewer university graduates, and most of them migrate to cities to search for job opportunities with a better income. OECD (2012) linked the rationing of

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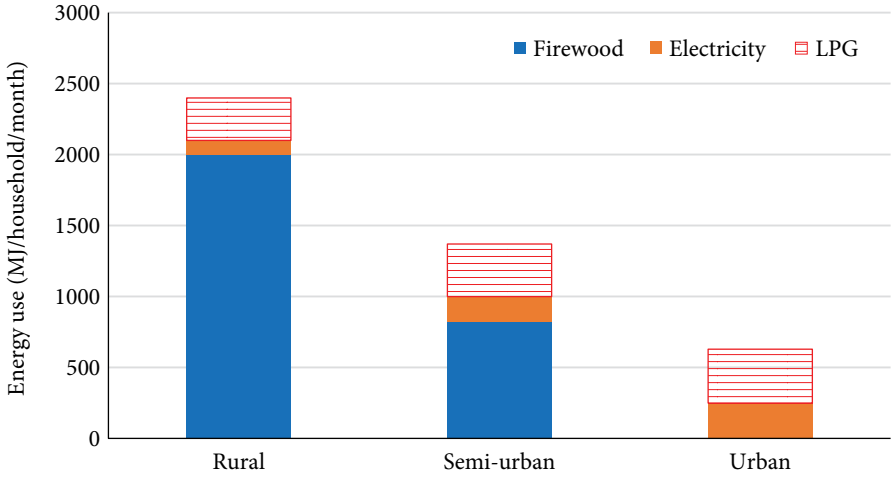

FIG. 15.3
Energy use in rural, semi-urban, and urban areas (1 MJ = 0.278 kW h).

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electricity consumption in a home in remote areas with the education level—to read and write—of the person in charge of the family. Boyle (2004) showed that the demand for electricity in the home is directly related to the education level of the household head. On the other hand, other researchers considered that the use of electricity in any household has nothing to do with the educational level of the family.

Figure 15.3 shows the energy use in urban, semi-urban, and rural areas in Nepal. The highest dependence on firewood for energy in rural areas is obvious (Fig. 15.4), the lowest dependence is for liquefied petroleum gas (LPG) consumption and electricity. In urban cities, there is no dependence on firewood as a source of energy, which confirms that the high level of income and the increase in the education level caused a change in the type of energy sources and the rationing of device consumption as aforementioned.

Concerning remote areas in developed countries, and despite the development and high level of income for families of these regions compared to developing countries, there are many similarities in terms of electricity consumption—especially in the islands belonging to these countries—although the scientific, educational, and economic levels of these regions make the share of renewable energy in consumed electricity different from the developing countries. Most of the world's islands are similar in terms of electricity generation, despite the randomness of production, the nature of the topographic islands, and the weather conditions that cause more complex problems than land conditions and are more complex for small islands compared to large ones. The reason for this dependent trend of

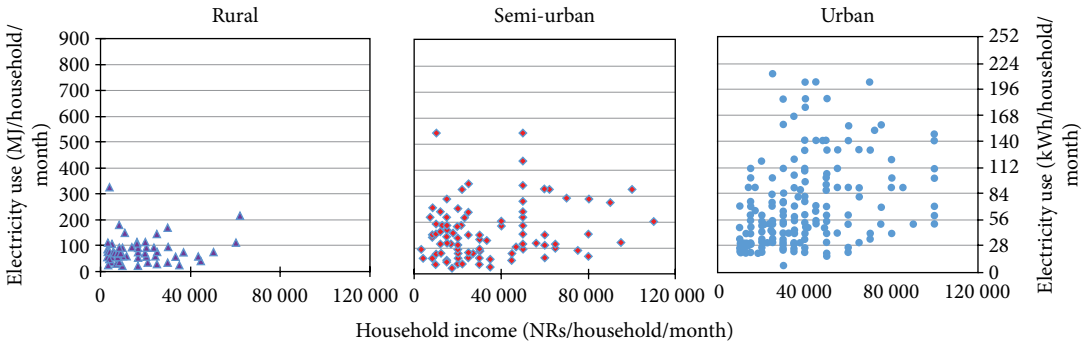

FIG. 15.4
Relationship between household income and electricity use.

renewable energies is the high cost of extending the national electricity grid lines, which stimulates the use of the islands' natural resources to generate electricity.

Most of the remote areas are not connected to the national electricity grid, and the process of imposing a supply/demand balance is very difficult owing to many factors. Usually, the number of inhabitants of remote areas is limited and scattered over large areas compared to the concentration of the population in small areas in cities. The electricity consumption in remote areas is highly variable, as the difference between the minimum/maximum demand for electricity is large. Hence, it was impractical to think of installing and operating large capacity plants. Hence, the use of power plants with small capacities enables them to withstand large variations between load and demand (Boyle, 2004). In some remote areas, especially some islands, their economy depends on seasonal tourism; so electricity consumption increases in the season of tourism (usually the summer), and the demand for clean drinking water increases, while this demand reduces highly in other seasons.

Most of the remote areas are using diesel generators to meet the electricity demand. Diesel fuel represents an economic burden because of its high cost, as it causes high pollution to the environment and harms public health. On the other hand, generators are suitable because of the high flexibility they provide according to the required capacities (Madsen and Andersen, 2010).

As can be seen from the above, at present, a major part of the electric power is met by generators running on fossil fuels. The cost of using these natural resources has become very high these days due to the increase in greenhouse gas emissions. Also, these sources have become a means of penetration. If we add to all this negative impact of high prices on the economies of the world countries, in addition to the cost of reducing or limiting the effects of pollution with the pollutants it emits, we find that it has become very expensive.

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Currently, attention is focused on renewable energy resources as an alternative to fossil fuels, and some consider them the best solution to reduce the greenhouse phenomenon and the serious environmental pollution resulting from burning fossil fuels to produce electrical energy. Systems operating with renewable energy sources are more environmentally friendly, efficient, and economical. These systems also provide an excellent and viable option for a fair and efficient distribution of electricity in remote areas. Several studies have advised the use of more than one application of renewable energy sources, such as wind, solar energy, hydropower, etc., in remote areas. Also, many scholars considered that relying on hybrid renewable energy systems that include two or more renewable energy sources, in addition to energy storage systems, is the best option for electrifying remote areas.

15.3 EFFICIENT TECHNOLOGIES FOR RURAL AREAS

When thinking about developing reliance on renewable energies to complement electrical systems and reduce dependence on fossil fuels, we immediately turn to the role of rural areas in this matter. Rural areas are areas with low population density because of the continuous migration to cities in search of sources of livelihood, while the population density is constantly increasing in cities, especially industrial ones. The increase in the urban population calls for an increase in energy consumption, while almost the opposite happens in rural areas where the energy demand is almost constant. Usually, rural and remote areas have great renewable energy potential compared to cities. Therefore, taking advantage of this potential—by converting rural and remote areas to green energy sources that can supply electricity to cities—is one of the solutions presented to researchers as an effective way to reduce greenhouse emissions and climate change. Power plants using renewable energies such as the sun and wind require large areas, so the implementation of such stations in the countryside calls for preserving productive agricultural lands and not wasting them on installing such stations (Madsen and Andersen, 2010).

The above scenario gives rural and remote areas high importance and a major role not only in food processing and production, but also in implementing plants and projects that rely on renewable energy sources as fuel. In the not-too-distant future, fossil fuels will not be able to guarantee global energy supplies, and serious consideration must be given to support national fossil fuel energy systems with power plants from renewable energies. This proposal is not easy, but rather needs a shift in the thinking of the political decision-makers. Such a measure could be a pivotal factor in combating climate change and offsetting any shortage of fossil fuel supplies (De Laurentis, 2012).

The problem with this typical solution, which can meet the demand for electricity in remote villages and rural areas, is to extend the central grid lines to these areas. Sometimes, the energy generated in remote areas is not economically feasible due to its remoteness and the engineering complications in connecting the grid to it. This is owing to its location and topographic complexities, as well as the distance separating this site from the nearest supply station of the central grid lines.

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The idea of generating decentralized electricity in remote areas represents a credible and highly effective approach among researchers (Li *et al.*, 2013a). Such decentralized stations that depend on renewable energy (wind energy, solar energy, and water energy) will contribute to the sustainable development in such areas and diversify their sources of income by creating new job opportunities for their residents. Such a procedure faces many complications resulting from the level of learning and the knowledge of advanced technology, in addition to providing a skilled workforce. Such a measure would make these regions autonomous in energy. But, if the appropriate conditions are provided, these independent regions with renewable energy systems can be linked to the central grid and turn into a provider of sustainable energy. Many experimental studies indicated that each country and region have its differences resulting from the introduction of advanced and modern renewable energy plant technologies.

Attention is now focused on generating electric energy from renewable energy sources. Research and development are being done on the production and construction of environmentally friendly, highly efficient, and cost-effective power generation systems. Green electricity production systems provide a suitable option to deliver electricity to rural and remote areas that suffer from a shortage of electricity supplies and to enrich these areas with one or more types of electricity production systems from renewable energies such as solar energy, wind, hydroelectric energy, etc. (Zhang *et al.*, 2019).

The use of sustainable renewable energies will greatly benefit rural and remote areas and in various fields, as follows:

1. Make the most benefit of the free natural energy resources available in those areas.
2. Purification and cleaning of the air in these areas from the exhaust pollutants of fossil fuel emitted by power generation systems, which makes these areas healthier and cleaner compared to cities.
3. Development of natural resources related to renewable energy.
4. Improving the environmental capabilities of remote areas and rural areas.
5. Increasing job opportunities, which reduces the migration of young people from these regions to cities and improves the quality of welfare for them.
6. Generating new income opportunities.
7. Diversification of rural economic activities.
8. Increase social cohesion.

The adoption of renewable energies as sources of electricity generation in rural areas and remote areas will have a positive impact on the national level and improve the economic strength of the country (Liu *et al.*, 2018). Power generation in rural areas with small and decentralized plants will improve the future of the desired, which is a low-carbon environment. These stations will contribute to solving local problems, in addition to meeting the increasing demands on local energy by using renewable energy owned by the local community without the need to import it. The local energy projects and projects supporting them will provide benefits to the residents of these areas in addition to the various companies, as the security of energy supplies will increase, which encourages them to open their

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branches in these areas (Recebli *et al.*, 2015). Here, one of the main causes of rural development will be its own ability to attract companies from outside the region.

From the above, the potential of renewable energies such as solar, wind, and biomass energies in rural areas is very large. The exploitation of these important resources will alleviate the problem of lack of energy supply in addition to greater protection of the environment. The increased dependence on renewable energy resources will provide good efficiency in reducing carbon dioxide emissions. These important resources will also contribute to the development of rural communities and increase their political and economic influence, thereby making them play a critical role in national energy security, improving the environment, and increasing job opportunities for citizens. Many countries of the world have focused great attention on developing sustainable green resources for power generation in their countryside. For example, in Poland, the state has taken an interest in producing electric energy from organic waste resulting from agricultural work, which is thrown by farmers. Practical experiments have achieved a level of electrical energy produced from sources of organic waste that could in the future lead these areas to energy self-sufficiency. In Pakistan, solid waste treatment methods have been used to solve the problem of energy shortage. The study conducted by Li *et al.* (2013b) found that developing the use of renewable energy sources to produce rural electricity is the most appropriate way to solve both the problems of electricity supply and environmental pollution in these areas. The study showed that the best response to the future of these regions with the challenges of energy security and environmental pollution is to use local electricity production systems that operate with more than one type of renewable energy. Here, we will focus on the most important green renewable energy resources in brief:

A. Solar energy: The use of solar photovoltaics on a large scale can be considered one of the best solutions to generate solar electricity in a manner that covers vast rural areas, and it is an application solution better used in rural areas than in cities. The use of photovoltaic cells in the countryside and remote areas on the roof of houses and departments, which spread over a large area, will facilitate the provision of electricity supplies to these buildings and their residents. From here, clean, green, environmentally friendly, and free energy, which is solar energy, is utilized to provide electricity. The efficiency of power generation in photovoltaic systems is affected by many factors of weather and the surrounding environment, such as the intensity of solar radiation, temperature, relative humidity, wind speed, dust, etc. Researchers studied the effect of each factor separately, but the mutual effects of the factors together, and were able to develop appropriate solutions for each specific situation. So the use of these systems has become common and accepted by both decision-makers and residents. For example, in China (in provinces such as Beijing, Tianjin, and Hebei), coal-producing electricity has been replaced by electrical generating systems distributed on the rooftops and government departments in rural and remote areas to alleviate the problem of electricity supply and improve the environmental conditions of these areas.
B. Wind energy: Rural and remote areas are sites rich in wind resources. As is known, the potential for generating electricity from wind energy available in these areas, in general, is great. Most of

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the countries of the world conduct a comprehensive survey of the wind resources on their lands to determine the best sites for installing wind farms. Wind power is affected by several conditions, including weather, climate, and site topography. The development of electricity resources from wind energy has had a certain impact on the spatial development of villages and cities. Research and development studies have suggested many solutions to such problems, thus improving and developing the wind energy industry without hindering spatial development.

C. Biomass energy: Biomass electricity can be produced from three main types of energy, namely, agricultural and forest biomass, garbage mass, and biogas. Several studies have shown that the potential for power generation of biomass resources in rural areas is very high. In Pakistan, rural electricity generation from biomass has been studied. The results of the study supported the possibility of using rural biomass to produce electricity that covers the countryside completely. This shift toward producing biomass energy will reduce the heavy economic impacts of importing oil and gas, and the high environmental impacts resulting from pollution of these areas with carbon emissions, causing a social and economic improvement for the residents of these areas. The use of biogas produced from animal dung instead of natural gas in home heating and cooking applications, in addition to electricity generation, has great environmental and economic benefits. In China, a study predicted that in the year 2050, the electricity produced from biomass extracted from major crops will be equal to the electricity generated from coal depending on the field yields, whether they are low, medium, or high. Malaysia was also able to take advantage of the highly decomposed municipal solid waste to generate organic bioelectricity. This method has resulted in extending the life of the landfill, reducing the use of fossil fuels in the production of electricity, and making the best use of alternative fuels. Many researchers have studied the establishment of plants for the disposal of animal waste and its use as biomass in the production of electricity.

In recent times, there has been a trend toward the use of hybrid renewable electricity generation systems that include two or more green systems linking them to various energy storage systems. This approach is promising to supply electricity to these rural and remote areas. These areas have an abundance of environmentally friendly renewable energy sources and are available for free. References Duman and Guler (2018) and Fodhil *et al.* (2018) considered that combining two sources such as solar and wind with natural complementarity is a cost-effective option. Such hybrid systems are a reliable option for delivering electrical energy to these areas. Hybrid renewable energy systems provide a highly reliable opportunity for rural electrification. Typically, a hybrid (off-grid) power system consists of a fossil diesel engine, one or more renewable energy systems, and/or an energy storage system (such as batteries or fuel cells). These hybrid systems have proven to be economical. However, research and development still have another important aspect, which is the development of energy management methods to ensure the efficiency and economics of hybrid renewable energy systems.

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15.4 EXPERIMENTS OF RENEWABLE ENERGY SYSTEMS IN RURAL AREAS

Many research studies have been conducted for energy use, management, and rationalization in designing hybrid renewable energy systems. For example, Duman and Guler (2018) used the HOMER program to evaluate the economic feasibility analysis of installing a hybrid renewable energy system operating in multiple climatic environments outside the grid. The study showed that such systems, with considerations of changing the surrounding environment, can electrify these areas effectively and at reasonable costs.

Mokhtara *et al.* (2020) reviewed several kinds of literature (up to 700 published research articles) that studied the use of hybrid renewable energy systems, and the research team concluded the following:

1. The majority of the studies focused on improving energy conservation before using hybrid renewable energy systems through population education.
2. Several studies focused on the criteria for the net cost of the system and the reliability of the system to operate in remote and rural environments, both technically and economically.
3. Most studies in the field of hybrid renewable energy systems considered that wind and solar energy systems are the best renewable energy resources for hybrid systems, while battery systems are considered the most suitable for energy storage.
4. Many studies focused on the supply and demand for electric energy and the potential of the proposed renewable energy organizations to ensure that this demand is met, especially during peak times.

In the following paragraphs, some international experiments in the field of hybrid renewable energy systems in rural areas are introduced.

15.4.1 Indian experience

India is considered to have characteristics related to rising population density, multicultural diversity, and the level of learning, which have severe impacts on social aspects and economic growth and places it in a completely different position from other countries of the world. Therefore, successive Indian governments have attached great importance to the use of renewable energies that the country has in producing electricity and integrating these systems into the central energy network. Since 1992, the ministry of electricity production has embarked on setting many measures such as an economic road map, policy, and research to reach a situation that enables the exploitation of renewable energy and its growth (EDF SEI, 2017; EDF SEI Saint-Barthelemy, 2017; and IRENA, 2017). Today, India is considered one of the world's leading countries in the field of using renewable energies to produce electricity, as it currently produces 20% of its electricity from renewable energy sources, according to

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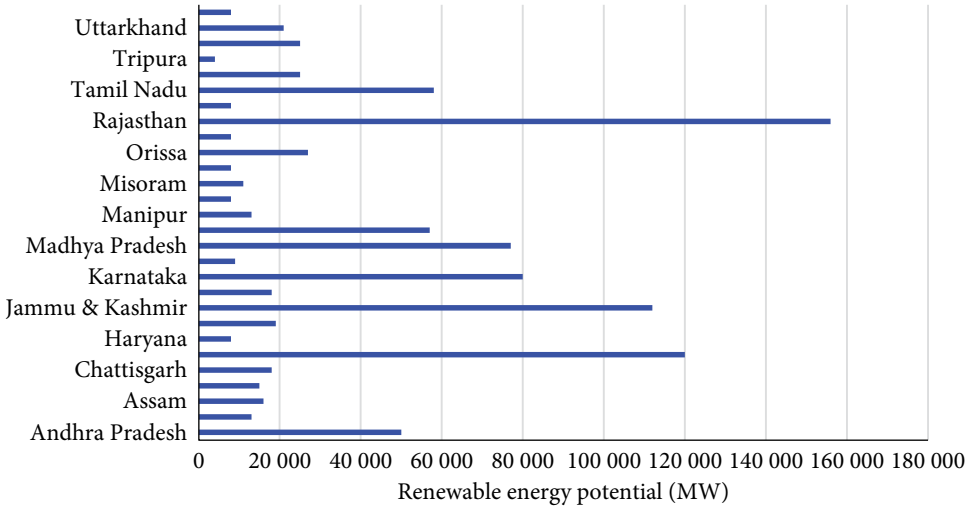

FIG. 15.5
The renewable energy potential of various states.

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the latest statistics in 2018. The electricity produced from wind energy has reached 34.98 GW (2018). The electricity produced from installed solar energy systems reached a capacity of up to 100 GW (2020). As for biomass, the systems for producing electricity from it reached 9.54 GW. Electricity generated from small water canals and rivers is an important resource for electricity in rural and remote areas in India, and the working capacity has reached 4.5 GW since 2018. Regarding the future plans in this field, the Indian government has set a goal to produce electricity by renewable energy systems in the range of 175 GW by 2022; this number represents 40% of the total electricity generated in this country. The Indian government is currently focusing on avoiding any emerging deficiencies in the energy systems and projects that have been established. Also, one of its most important goals is to integrate climate-friendly renewable energy sources into the electricity production systems to reduce the country's dependence on imported fossil fuels, which represents a burden on the state treasury. The Indian government has also begun to stimulate the deployment of wind and solar power stations as decentralized electricity production systems to enhance reliance on renewable energies (Fig. 15.5).

India's countryside has a high concentration of people in dispersed and scattered villages, and a large number of Indian citizens live in remote areas without access to the network. The delivery of grid electricity to such areas is not possible in terms of the heavy economic costs to the state, but there is a practical and logical option in installing independent hybrid renewable energy systems. Ramesh and Saini (Department of Mayotte, 2017) analyzed a hybrid renewable energy system installed in a remote rural area located in the state of Karnataka. The system studied consists of photovoltaic panels, wind turbines, water turbines, a diesel generator, and a battery system. The results of the study concluded that

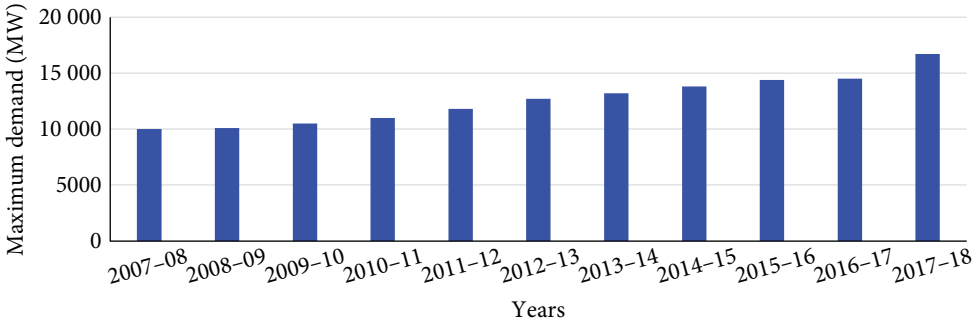
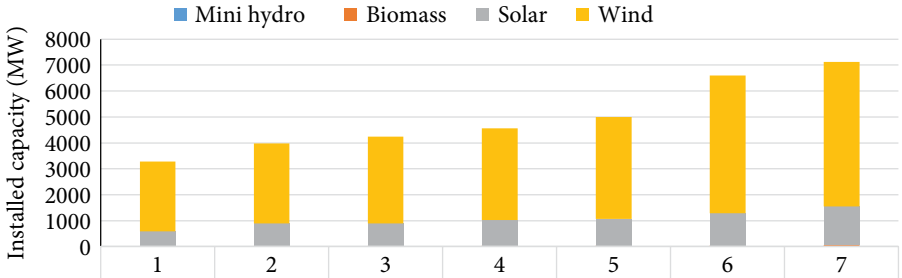


FIG. 15.6
Maximum demand.

such a system is feasible in terms of energy costs. Also, the use of lithium-ion batteries in the hybrid system results in the lowest operating costs (Figs. 15.6 and 15.7).

15.4.2 The French experience

The French government controls about 1300 islands located in various parts of the world that are spread in the arctic and southern polar regions as well as in the tropical spaces. Perhaps, the largest of these



	1	2	3	4	5	6	7
Wind	2695	3087.4	3351.95	3541.68	3932.73	5319.38	5574.75
Solar	554.5	856.51	850.8	973.54	1015.86	1229.6	1493.31
Biomass	31.2	31.2	31.2	41.1	41.1	41.1	41.1
Mini hydro	0	6	8.56	8.56	8.56	8.56	20.56

Years

FIG. 15.7
Installed renewable energy capacity.

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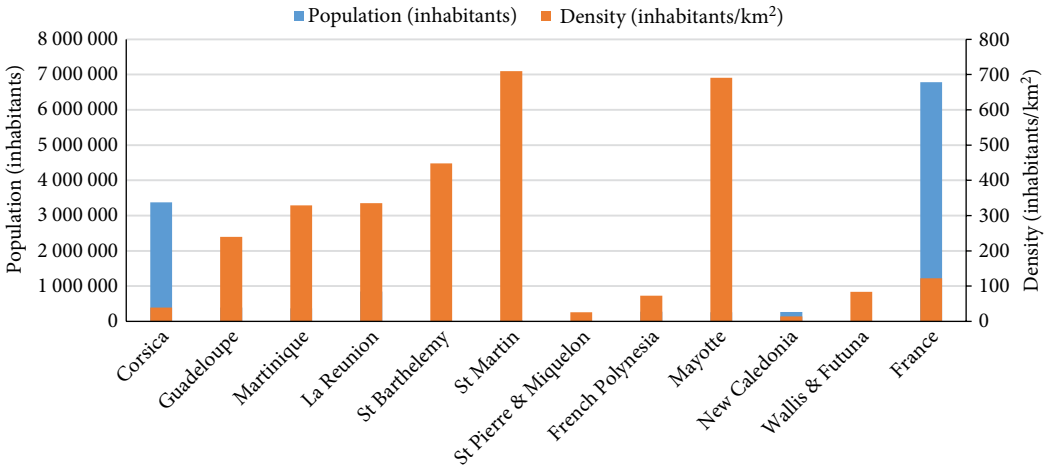

FIG. 15.8
Population and density for the main French islands.

islands in area and population density is the island of Corsica. Figure 15.8 gives details of some of the most important islands around the world. The French islands vary greatly in terms of area, population, and location, and this diversity is followed by great differences in geographical, topographical, and meteorological conditions. In general, these islands are not connected to the mainland's electricity network. Therefore, most of these islands suffer from a weak energy situation and low processing hours (Yang *et al.*, 2017). The number of inhabitants in these islands is small as shown in Fig. 15.8, which makes the electricity consumption according to the seasons of the year uneven, for example, on the island of Corsica, the electricity consumption in May is about 130 MW, and the maximum electricity consumption is in December (up to 500 MW).

Some islands face a problem of another kind since these islands subsist on tourism in their economy. Therefore, in many cases, the seasonal demand for energy is great. In such cases, the demand for electricity is high during the tourism season. In this season, hydroelectric power is either completely unavailable or weak. The demand for drinking water is also clearly increasing. In most of the French islands, diesel generators are approved to generate electricity and supplement the networks there. As it is known, diesel fuel is economically expensive and its emissions cause high pollution to the environment, but on the other hand, it provides generators with suitable sizes that enable the load change to be controlled. The French government issued an order on 23 April 2008, limiting all systems that work without a connection to the grid to be 30% of the electricity generated through renewable energy systems, to ensure the safe supply of electricity to these islands. Some French islands have high hydroelectric potential but are only available on a few. Generating electricity from photovoltaic systems

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is more successful than generating it from wind energy, as 80% of the renewable electricity is produced from photovoltaics, while 20% is from wind energy. This disparity can be attributed to the difficulty of installing large wind turbines in limited runways for environmental and technical reasons.

15.4.3 China experience

China has the highest population in the world, mostly concentrated in vast rural areas. China is also the largest consumer of electric energy in the world, accounting for 23.2% of the world's electricity consumption. Most of the power plants operate with coal and oil, and they cause high pollution and carbon emissions around a third of what the world produces as a whole from carbon emissions (Wang and Jiang, 2017). Environmental pollution has increased in rural areas due to the high consumption of energy and has affected the economic development and social life of the inhabitants here with the increase in electricity demand. Rural people in China have switched from using traditional fuels, such as firewood and other agricultural waste, human and animal waste, to using electricity produced from fossil fuels. The Chinese government aims to educate rural people to switch from traditional to renewable energy. China relies on this approach to change the thoughts of families there through education and family structure (Fig. 15.9).

The current policy of the Chinese government is to provide electricity to rural homes and to educate individuals on rationing consumption and saving electricity. For this purpose, the Chinese government has launched several electricity production projects with photovoltaic power stations. It has also developed a plan that will last for six years, starting in 2014, aimed at alleviating poverty in the countryside through subsidies and income generated by photovoltaic electricity generation. This plan alleviated poverty for about 2×10^6 rural families in 35 000 villages.

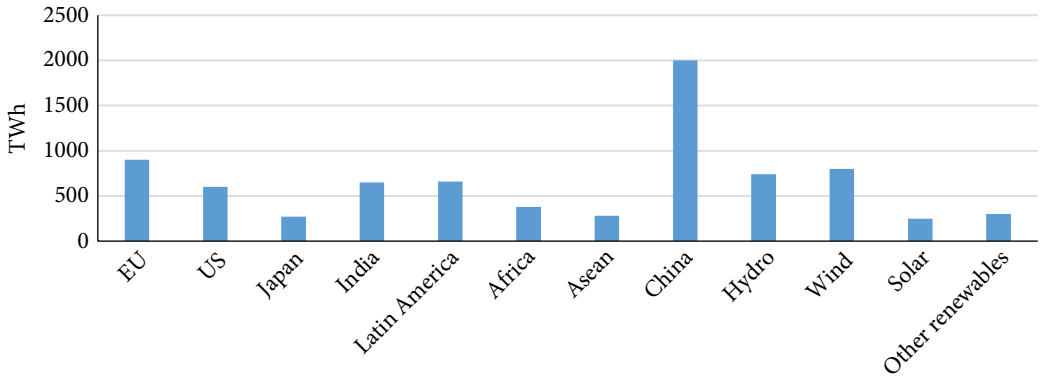

FIG. 15.9
Increment electricity generation from renewables in selected regions, 2011–2035.

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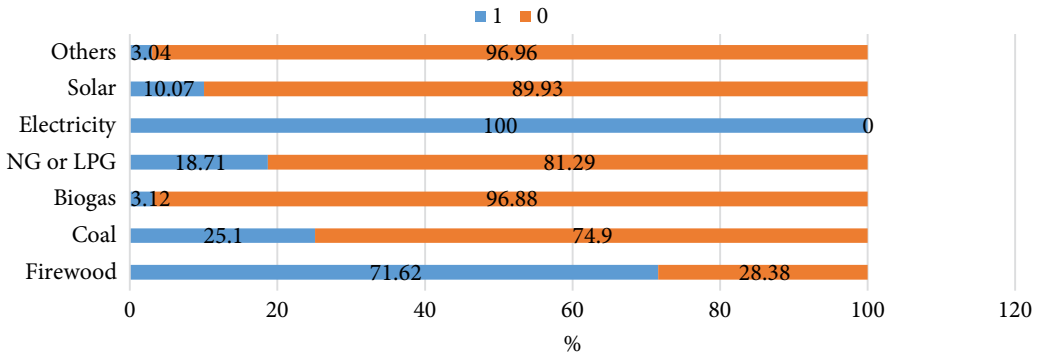

FIG. 15.10
The proportion of the household energy choice.

PPAPs covered 30 Chinese provinces in 2014, with a renewable electricity capacity of 5.16×10^6 KW in 2016, produced from home PV and rural PV plants. In 2017, an amount of 4.18×10^6 KW was added to this production. The authors of Wang *et al.* (2017) expect that the PPAPs will provide a better future for China's rural population. In practice, the PPAPs have made remarkable advances in some areas (Fig. 15.10).

Note: when the household chooses a certain energy type, the value is 1, otherwise the value is 0.

15.4.4 The Kenyan experience

In 2017, the International Energy Agency (WEO) estimated that 1.1×10^9 people (approximately 14% of the world's population) do not have access to electricity and that more than 95% of this number is concentrated in Africa (sub-Saharan countries and Asian countries). Kenya, an African country, managed to improve the electricity production situation to reach 47% of the country's electrification in 2016 (Kenyatta *et al.*, 2013). This country faces many challenges in the field of electricity and its supply to all regions of the country. The most important of these challenges are the following:

1. The weakness of the electricity network in reaching large areas of the country, which makes rural residents focus on using biomass resources for cooking.
2. The electricity cost in Kenya is high.
3. The energy demand is increasing compared to the rate of installing new plants to generate it.
4. The cost of extending the electrified grid to the countryside is very high due to the dispersal and remoteness of the villages.
5. The systems in place today depend on fossil fuels to produce electricity.

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The Kenyan government has set a roadmap to raise the standard of living for the Kenyan citizens and indicated that the most important factor to reach this goal is to provide electrical energy. Since 2004, the Kenyan government has sought to change its power generation policy to reach 40% of rural Kenyan electricity. The Kenyan government has intended to set up and operate diesel-powered power stations that are not connected to the grid or linked to small, limited distribution networks to cover the needs of rural or remote villages, which is practical, but not economically feasible to connect to the national grid. These diesel plants suffered from many challenges, such as:

1. The high cost of fuel as a result of transportation to remote locations.
2. The high cost of storing fuel at this location.
3. High operating and maintenance costs.
4. The high level of environmental pollution that results from the burning of fossil fuels in these areas.

In 2017, the Kenyan government experimented with generating electricity from hybrid power plants that are not connected to the grid, powered by renewable energy resources such as wind and solar energy. Currently, experimental stations consist of diesel generators, in addition to hybrid systems that operate with photovoltaic panels or wind, as well as those powered by both solar and wind energy out of the grid.

15.4.5 North Korea experience

North Korea is one of the countries with a low electricity production rate and covers the demand of 27% of its citizens. The situation is worse in rural and remote areas, which cover only 11% of the electricity demand. The North Korean electricity sector suffers from an aging electricity infrastructure (Li *et al.*, 2013a). This country ranks low in relation to Asian countries and the world in this regard. North Korea suffers from a chronic deterioration in its electricity supply, most of which relies on traditional fuels such as coal. Coal along with hydroelectric power are the two main sources of electricity in the country. Excessive dependence on these two sources has resulted in a great depletion of natural resources and the destruction of the environment. Starting in the year 2000, the North Korean government built several dams to increase the generation of electricity. Dams have raised the electrical capacity produced, but their environmental impacts have been catastrophic. They caused great damage to the ecosystem and frequent landslides (Liu *et al.*, 2018). Also, because the country has a large wealth of coal, the reliance on coal to generate electricity has increased, and reached 50% of the total energy generated (Recebli *et al.*, 2015). Currently, rural residents in North Korea depend on biomass to provide energy (Liu *et al.*, 2018). This dependence added to an environmental burden due to excessive logging that resulted in deforestation (Figs. 15.11 and 15.12).

The North Korean government, through its projects to electrify the countryside, has adopted the traditional way of problem dealing by extending the electrical network. This caused an increase in environmental damage resulting from the heavy reliance on fossil fuels to produce electricity. Kwak (2018) indicated that the North Korean government is considering enacting laws and policies to introduce a mini-grid system.

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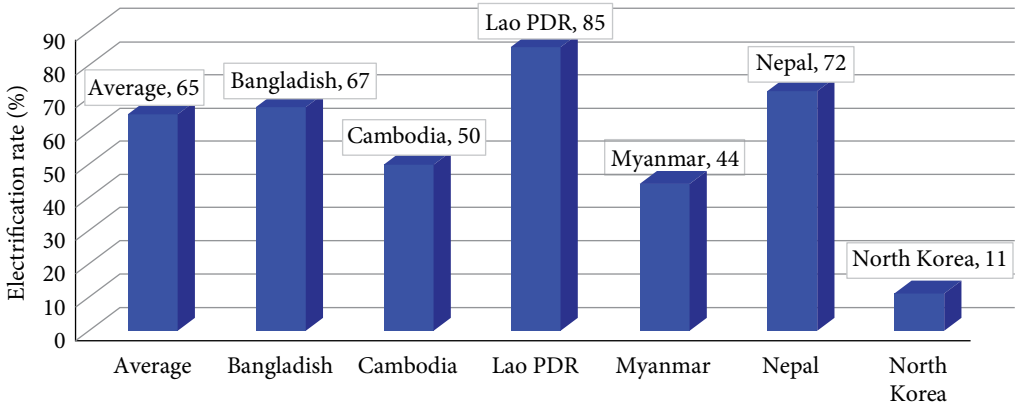

FIG. 15.11
Rural electrification rate of developing Asian countries.

Also, now an increasing number of solar panels are being installed on the roofs of homes and commercial buildings in the country. The study concluded that the reliability of PV systems is high in North Korea. The study by Kwak (2018) also confirmed that North Korea is rich in renewable energy sources, thereby making the future of renewable energy systems bright in the country. Using HOMER, the authors of Qiu *et al.* (2015) designed a project to electrify a rural village in the country. The researchers studied the best cost-effective hybrid power system, comparing both the grid and off-grid systems. The study concluded that a hybrid electric system consisting of diesel generators, PV, wind turbines, and lead-acid batteries is the most appropriate option when taking into account the cost and location of the construction. The use of decentralized networks of limited dimensions from 9.69 to 20.57 km is a suitable way to improve the electricity situation in the remote and rural areas of North Korea.

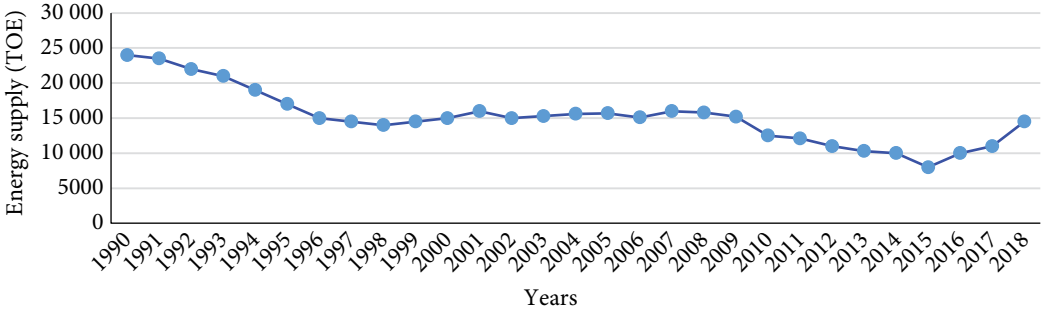

FIG. 15.12
Trend of the energy supply in North Korea.

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15.5 CONCLUSIONS

From the previous review, replacing the national grid with renewable energies to produce electricity in remote areas is the best solution to this dilemma. This method will improve the future of the regions and make them an environment with low carbon emissions, and it will also contribute to meeting the increasing electricity demand.

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Renewable Energy: Analysis, Resources, Applications, Management, and Policy is a comprehensive overview and examination of the latest analysis, resources, applications, management, and policy of this emerging area of study. It offers solutions to overcome hurdles in implementing renewable energy technologies and brings together a broad range of technologies in a single source including solar-, wind-, hydro-, tidal-, geothermal-, and biomass-based energy.

This important book:

- Reviews renewable energy types to provide economic, environmental, and social solutions that support national economies
- Examines ways to overcome hurdles in implementing renewable energy technologies
- Discusses international challenges such as contamination, desertification, and poverty in application and management strategies

Renewable Energy: Analysis, Resources, Applications, Management, and Policy will appeal to a wide range of postgraduates and undergraduate researchers. Professionals in the field will find it a helpful resource and valuable reference.

Yarub Al-Douri, Ph.D., is Professor of Nanotechnology at the American University of Iraq, Sulaimani, Iraq, where he founded the Nanotechnology Engineering Master's program. He founded the Nano Computing Laboratory in Malaysia and is the recipient of numerous research awards from Austria, Japan, China, and others. He is Associate Editor of *Nano-Micro Letters* (Springer) and Editor-in-Chief of *Experimental and Theoretical NANOTECHNOLOGY*. He authored over 322 journal articles and 16 book chapters. His extensive research career has spanned throughout Europe, Asia, and Africa. Editor.

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